

**Development of a wind turbine emulator
control system**

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Gaia Wind premises in Glasgow (with pylon in the background)

Abstract

Wind turbine design and development is currently a very dynamic industry, and designers need appropriate tools and resources to experiment with innovations and to evaluate the effect of modifications. However, access to installed turbines in situ for testing and monitoring is typically difficult. Hardware-in-the-loop simulation offers a solution to this problem. A wind turbine emulator uses a real or scaled-down drive train but typically replaces the prime mover with an electric drive.

Based on a review of previous work on wind turbine emulators, this project proposes a control system designed to reproduce a variable wind profile taking into account torque oscillations due to wind shear and tower shadow.

Initial software development is undertaken to provide a basic human machine interface to emulator hardware. The software does not attempt to implement the turbine model at this stage.

Results from evaluation and software testing identify limitations of the current configuration. A series of follow-on projects is outlined.

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Symbols and abbreviations

Symbols

A	Swept area of turbine rotor (m ²)	V	Actual velocity of air stream (m/s)
CP	Power coefficient	V ₀	Wind velocity at reference height h ₀ (m/s)
CQ	Torque coefficient	V _h	Wind velocity a height h (m/s)
D	Aerodynamic drag force	W	Width of tower shadow
d	Direct component of stator current (A)	x, y, z	Linear distances (m)
f	Distribution network frequency (Hz)	Z	Aerofoil zero lift line
J _{generator}	Moment of inertia of generator rotor (kg m ²)	z ₀	Ground roughness length
J _{rotor}	Moment of inertia of turbine rotor (kg m ²)	α	Angle of attack (rad)
L	Aerodynamic lift force	β	Blade pitch angle (rad)
n	Gear ratio (n:1)	Δ	Maximum airstream velocity deficit
N	Number of poles in EM	η	Efficiency
ns	Synchronous speed	η _d	Drive efficiency
P	Power (W)	η _{dgb}	Drive gearbox efficiency
Q	Torque (Nm)	η _g	Generator efficiency
q	Quadrature component of stator current (A)	η _{ggb}	Generator gearbox efficiency
Q _{corr}	Corrected torque	η _u	Efficiency factor for unknown losses
Q _{drive}	Torque associated with EM drive (Nm)	λ	tip-speed ratio
Q _{err}	Torque error	ρ	Density of air (1.225kg/m ³ at sea level)
Q _{generator}	Torque associated with generator (Nm)	Φ	Wind direction relative to rotor plane (rad)
Q _{mech}	Mechanical torque	φ	Azimuthal turbine blade angle (rad)
Q _{ref}	Reference torque	Ω	Angular velocity of turbine rotor (rad/s)
Q _{rotor}	Torque associated with turbine rotor (Nm)	ω	Angular velocity of drive train component (rad/s)
R	Radius of turbine rotor (blade length) (m)	ω _{generator}	Angular velocity of generator rotor (rad/s)
S	Slip	ω _r	Angular velocity of EM rotor (rad/s)
T	Tower diameter (m)	ω _s	Angular velocity of stator magnetic field (rad/s)
U	Uninterrupted wind speed (m/s)		

Abbreviations

AC	Alternating current
CPU	Central processing unit
CRC	Cyclic redundancy check
DC	Direct current
DFIG	Doubly fed induction generator
EM	Electromechanical machine
EMI	Electromagnetic interference
FITS	Feed-in tariff scheme
FOC	Field-oriented control
HAWT	Horizontal axis wind turbine
HIL	Hardware-in-the-loop
HMI	Human machine interface
HSS	High speed shaft
HUT	Hardware under test
IEC	International Electrotechnical Commission
IGBT	Insulated gate bipolar transistor
LSS	Low speed shaft
NMEA	National Marine Electronics Association
NREL	National Renewable Energy Laboratory
PC	Personal computer (Windows)
PHIL	Power hardware-in-the-loop
PI	Proportional-integral
PID	Proportional-integral-derivative
PLC	Programmable logic controller
PMSM	Permanent magnet synchronous machine
PWM	Pulse width modulation
SCIM	Squirrel cage induction machine
STP	Shielded twisted pair
USB	Universal Serial Bus
V/f	Voltage/frequency
VFD	Variable frequency drive
VVW	Voltage Vector Weg
WLP	Weg ladder programming
WTE	Wind turbine emulator

Units

A	Ampere (current)
kWh	kilowatt-hour (energy)
m	metre (distance)
N	Newton (force)
rpm	Rotations per minute
s	second (time)
V	Volt (potential difference)
W	Watt (power)

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1 Introduction

1.1 General

Wind turbine design and development is currently a very dynamic industry. With the increasing costs associated with traditional fuels, the extraction of energy from a renewable resource like the wind is extremely attractive. To maximise the value of such extraction, the efficiency of turbine designs from the aerodynamics of the blades to the software that controls their operation is paramount. Designers need appropriate tools and resources to experiment with innovations and to evaluate the effect of modifications. Because wind resource is typically most abundant in remote and inaccessible places, monitoring and testing in situ is difficult. Simulation offers a solution to this problem, but although software simulation is becoming quite sophisticated, building an adequate software model can be very time-consuming and expensive. An alternative is to use the hardware in the loop (HIL) approach in which real or scaled-down turbine hardware is used with a simulated wind resource. Such a system can be referred to as a wind turbine emulator (WTE). This project focuses on the requirements for an effective WTE through an exploration of the relevant background literature and a practical development exercise.

1.2 Aims and objectives

The aim of this project is to establish a basic control system for a WTE. In order to do this, the following objectives will be addressed:

- A review of current relevant literature
- An investigation of the capabilities of a specific hardware configuration
- The specification and development of a software application to provide a human machine interface (HMI) and communications with the hardware components
- An examination of the limitations of the developed application
- The definition of a series of future projects that build upon the current work

1.3 Structure of report

Chapter 2 of this report summarises the main relevant aspects of wind turbine design and operation and ends with a review of previous WTE studies. Chapter 3 discusses the methods used during the project and summarises some of the organisational processes. Chapter 4 presents the results of the project work, while chapter 5 outlines a series of potential follow-on projects based on this work. Chapter 6 summarises the conclusions from the project and includes a personal reflection on the project experience. Appendix material follows, and the list of references is positioned at the end for easy access.

2 Literature review

This section explores a range of aspects of wind turbine design that need to be taken into account when constructing a WTE. The section ends with a review of previous work on WTEs.

2.1 Wind energy context

Although wind energy has been used for centuries to do useful work such as driving ships and grinding grain into flour, it is only since the oil crisis in the 1970s that it has been considered as a serious candidate for electricity generation (Gross, 2007).

Today, energy security continues to be a major driver for the development of wind energy devices, along with the abatement of airborne pollution from fossil fuel power stations and combating climate change. Because of these pressures, the market for wind turbines has shown over 20% growth every year since 1998 and total worldwide installed capacity reached 196.63 GW in 2010 (WWEA, 2011). This strong growth is illustrated in Figure 1.

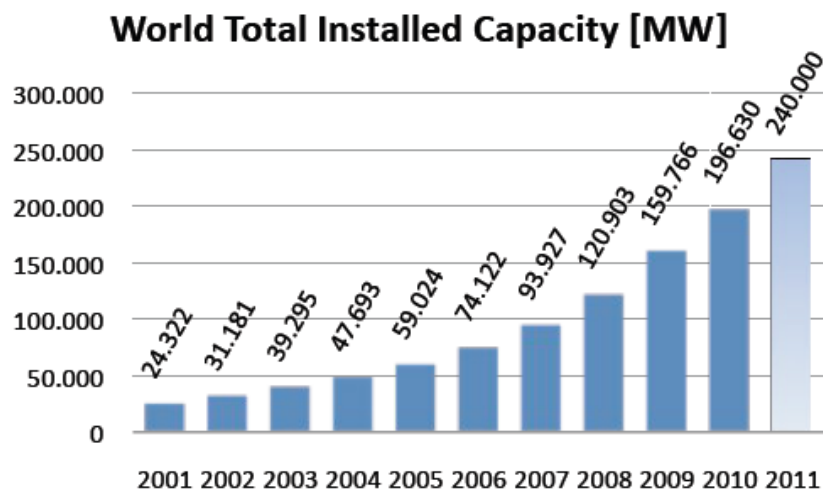


Figure 1: World wind turbine installed capacity (WWEA, 2011)

Focussing on the situation in Europe, a recent report by RenewableUK (previously the British Wind Energy Association) shows a very uneven deployment of turbines. Whereas Denmark and Germany have relatively high turbine densities at eleven and six turbines per hundred square kilometres respectively, the UK has just over one (RenewableUK, 2011). The UK therefore currently lags behind other European countries despite its richer wind resource; however, the UK government's target of

producing 15% of its electricity from renewable sources by 2020 (DECC, 2010) would require among other things that onshore turbine density increases to around 2.44 turbines per hundred square kilometres (RenewableUK, 2011). The market for wind energy in the UK is therefore promising in the short term with its underexploited capacity and positive economic pressures.

There are wide differences in the deployment of turbines among the constituent nations of the UK. Scotland already sources 15% of its electricity from wind and accounts for 61% of UK installed capacity while making up only 32% of its geographical area (RenewableUK, 2011).

Country-level statistics are typically based on the deployment of multi-megawatt turbines in windfarms, and much effort goes into the design of turbines with larger and larger capacity in order to better exploit the resource at a particular site. One of the largest turbines currently deployed, for example, is the 7.5 MW Enercon E126, while several larger units are currently under development and will be delivered in the next few years. The Azimut consortium led by Spanish company Gamesa aims to deliver a 15 MW turbine by 2014 (Gamesa, 2010). At the other end of the scale, however, the development and deployment of smaller turbines also shows strong growth. A market report by RenewableUK describes an extremely active industry in which installed capacity in the UK rose 65% during 2010 from 8.62 MW at the beginning of the year to 14.23 MW at the end (RenewableUK, 2011b). One of the factors that contributed to this growth was the introduction in April 2010 of feed-in tariffs (FITS) as a financial incentive for small-scale renewable electricity generators (DECC, 2011). Under the scheme, the operator receives a payment for generating electricity, which currently ranges from 4.7 to 36.2 pence per kilowatt hour depending on the installed capacity. If the generated electricity is also exported to the grid a second payment is made of 3.1 p/kWh. A rough calculation shows that for a 10 kW turbine costing around £40000 and operating at a modest 15% capacity factor the FITS payments would mean a financial payback period of approximately 10 years. This makes small scale wind generation an attractive investment for small landowners such as farmers. Table 1 summarises RenewableUK's classification of turbine sizes and the corresponding FITS rates for a single turbine. Note that the FITS scheme has additional bands with lower rates which allow for the installation of

multiple turbines. The largest capacity allowed under the scheme is 1.5 MW for which the rate is 4.7 p/kWh.

Category	Rated power (kW)	Installed cost (£k)	FITS rate (p/kWh)
Micro	0 – 1.5	0.5 – 5	36.2
Small	1.5 – 15	2 – 50	28
Small-medium	15 – 100	50 – 250	25.3

Table 1: Turbine categories and corresponding FITS rates (RenewableUK, 2011b; Ofgem, 2011)

2.2 Turbine design issues

The effective design of wind turbines relies on detailed knowledge of several distinct subject areas which are briefly summarised in the sections below.

2.2.1 Conceptual design

All wind turbines operate by using a proportion of the kinetic energy in an air flow to develop torque in a shaft. Early European windmills drew upon the seafaring experience of the local cultures and used sails to drive the shaft. Although arrangements with many sails were possible, the typical design was based on four sails to simplify the construction of the supporting frame (Burton et al., 2001, p.340). All current designs rely on more or less rigid rotors based on the principles of aerodynamics, and usually have two or three rotor blades mounted on a horizontal axis. Vertical-axis designs are also in use, but they are less popular due to their lower efficiencies and higher cost (Gross, 2007, p.104). The explanation for the design convergence in horizontal-axis machines requires reference to some basic theoretical concepts.

As for any other energy conversion device, it is important to have a means of expressing the efficiency of a wind turbine. Fundamentally, this is ratio of the actual power production of the machine to the total energy available, and gives a dimensionless power coefficient, C_P , whose basic formula is given by Eq. 1.

By optimising the formula for C_P , it can be shown that the maximum possible value is 0.593, known as the Betz limit. Because the Betz limit is derived from theoretical principles rather than with reference to any particular turbine design (Burton et al., 2001, p.45), it provides a fixed upper bound for the efficiency of any turbine. The actual value of the power coefficient is affected by the geometry of the rotor blades

and also varies with wind speed. The interaction of these quantities can be captured with reference to another proportional characteristic known as the tip speed ratio, λ . The tip speed ratio is defined as the tangential velocity of the spinning rotor divided by the velocity of the uninterrupted wind as given by Eq. 2.

$$C_P = \frac{\text{Output power}}{\frac{1}{2}\rho U^3 A} \quad (1)$$

where ρ is the density of air (1.225 kg/m³)

U is the wind velocity (m/s)

A is the circular area swept by the turbine blades (m²)

(Burton et al., 2001, p.44)

$$\lambda = \frac{\Omega R}{U} \quad (2)$$

where Ω is the angular velocity in radians per second

R is the rotor radius in meters

(Burton et al., 2001, p.49)

The power coefficient can be plotted against tip speed ratio for a given turbine design to give a characteristic performance curve. Figure 2 shows this curve for turbines with different numbers of blades, from which several observations can be made (Burton et al., 2001, p.175):

- Fewer blades produce a broad, flat curve where C_P remains roughly constant over a wide range of λ , but the maximum value of C_P is low.
- More blades give a higher maximum value for C_P , but the curve has a narrow peak making the design sensitive to changes in λ .
- A design with three blades produces the highest maximum C_P , but a two bladed design gives more consistent performance over a wider range of λ .

It should be noted that the curves in Figure 2 assume that the blades themselves are of similar dimensions in each case.

A further performance measure which is commonly used is the torque coefficient, C_Q . Burton et al. (2001, p. 64) provide a derivation of turbine torque from first principles, and also state that the torque coefficient can also be calculated by dividing the power coefficient by the tip speed ratio for a given wind speed (Burton et al., 2001, p.176). Thus it does not give any more information than the power coefficient, but can be useful in determining instantaneous torque Q using Eq. 3

$$Q = \frac{1}{2} \rho \pi R^3 U^2 C_Q \quad (3)$$

(Teodorescu et al., 2003)

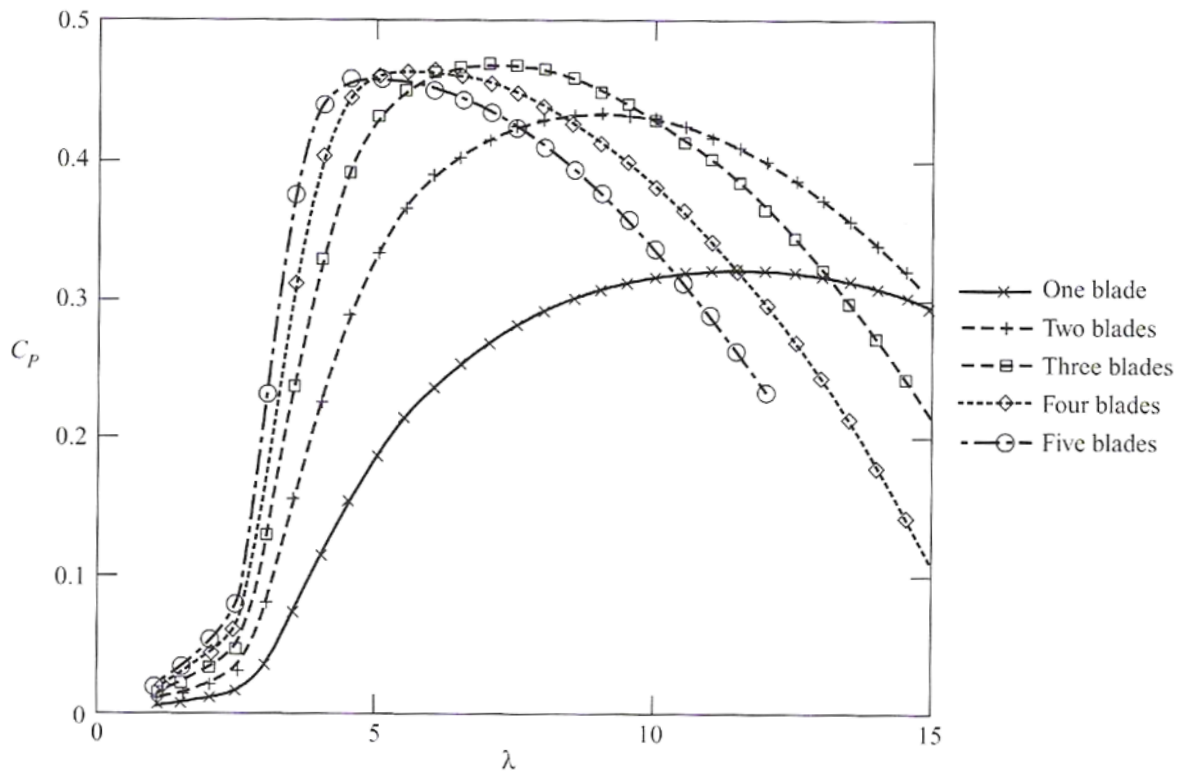


Figure 2: Effect of blade number on performance (Burton et al. p. 175)

A limitation of Burton's simple relationship between C_P and C_Q is that it does not account for the existence of a non-zero torque at standstill (Teodorescu et al., 2003). An alternative presented in the literature is produce a C_Q - λ curve from test data

(Lopes et al., 2005; Weiwei Li et al., 2007; Munteanu et al., 2008) which leads to a polynomial expression for C_Q as a function of λ . In their derivation of C_Q , Yaoqin Jia et al. (2007) assume a value for startup torque as a given parameter, while Weiwei Li et al. (2007) also suggest using a lookup table which amounts to the same thing.

2.2.2 Blade design

It should be acknowledged from the outset that any brief consideration of the design of turbine blades requires many simplifying assumptions. Issues such as the non-uniformity of air flow in real situations, the smaller aerodynamic effects that occur at specific points on a blade, and the variation in blade geometry along its length are all worthy of exploration. For a detailed look at such issues, please refer to Burton et al. (2001).

The cross section of a rotor blade at any given point along its length can be modelling in two dimensions as a standard aerofoil. The characteristic shape of an aerofoil gives rise to the phenomenon of aerodynamic lift when air flows over it at a given angle. The lift force acts at right angles to the actual air flow, while a second component of the total force on the aerofoil known as drag acts in the same direction as the air flow. Figure 3 summarises the aerodynamic forces on an aerofoil set at a given angle α to the incident air flow. This is known as the angle of attack, and variations in α have a large effect on the relative sizes of the lift and drag forces. Specifically, once the angle of attack reaches a critical value of around 10° to 16° , the behaviour of the air flow leads to the drag force outweighing the lift force, and the aerofoil is said to be in stall (Burton et al., 2001, p.166).

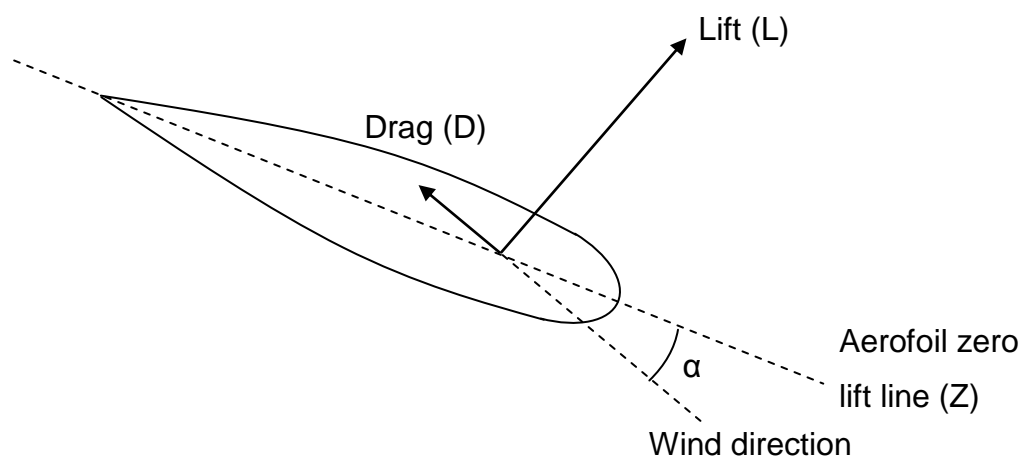


Figure 3: Aerofoil lift and drag forces (Adapted from Burton et al., 2001, p. 61)

Because the blades of a wind turbine are rotating, an air flow is also induced in the opposite direction to the rotation, which is to say perpendicular to the air flow due to the wind. It is common therefore to talk about the vector sum of these two flows as the air flow *experienced* by the rotor blade. It is the angle of attack relative to the resultant air flow which is relevant when calculating the forces on the blades of a rotating turbine, and Figure 4 shows its derivation. Also shown in Figure 4 is the blade pitch angle, β . The pitch angle is significant because it is a controllable design parameter whereas the angle of attack varies with local conditions.

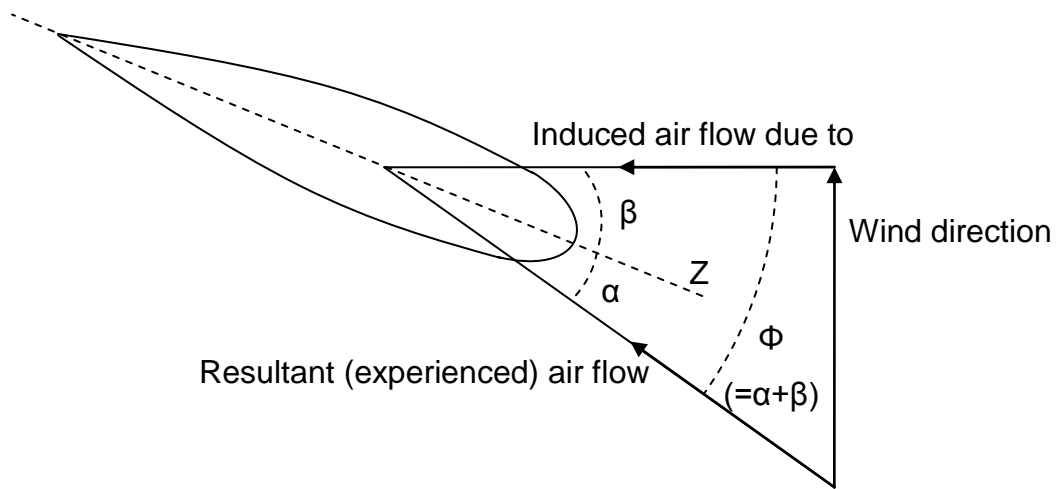


Figure 4: Resultant airflow on rotating blade (Adapted from Burton et al., 2001, p. 61)

Because we are interested in the torque applied to the rotor shaft, a final decomposition of the lift and drag forces is required to determine the component that acts in the direction of rotation. By simple vector decomposition, this turns out to be

$$L \sin \Phi - D \cos \Phi$$

where L and D are the lift and drag forces, and Φ is the angle between the airflow experienced by the blade and the plane of rotation (ie $\alpha + \beta$). This decomposition is shown in Figure 5 which also shows the considerably larger force acting perpendicularly to the plane of rotation (Burton et al., 2001, p.61).

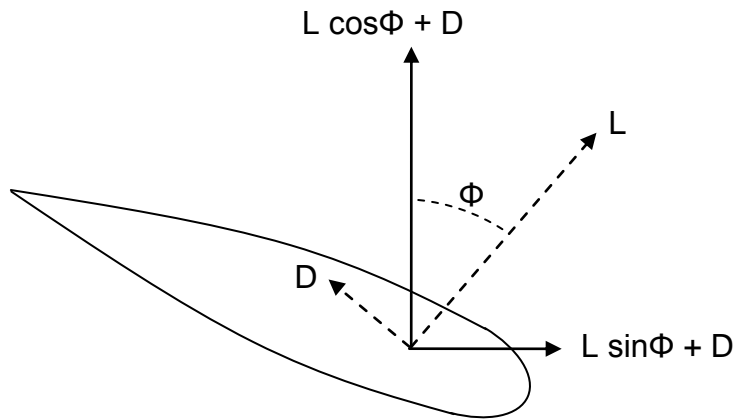


Figure 5: In-plane and out-of-plane forces on turbine blade (Adapted from Burton et al., 2001, p. 61)

The actual aerodynamic behaviour of the rotor blades depends on their detailed design features. Some of the parameters that can be modified are the rotor radius, the width of the blades at different points along their length, the variation in the pitch angle along the blade length and the degree of camber in the aerofoil cross section.

Although it is the aerodynamic construction of the blades that determines the torque they generate, the mathematical complexity involved is considerable. In practice, the torque developed by a rotor is typically calculated on the basis of empirical measurements.

2.2.3 Materials

The choice of materials for a machine of any kind is driven by several potentially conflicting goals. The performance of the machine should be maximised, which in the case of a wind turbine means for example that the blades should be as light as possible. At the same time it should be robust enough to resist damage under extreme conditions (Burton et al., 2001, p. 377). A trade-off is therefore required to balance these requirements. In the case of the rotor, this has a significant effect on the behaviour of the machine. The rotor is subject to a range of forces, some of which are required for its successful operation. Other forces such as the component of the aerodynamic force perpendicular to the plane of rotation are actually undesirable but nevertheless have to be accommodated. In general, there are two significant categories of forces that need to be taken into account: bending moments which arise from the long thin shape of the typical rotor, and fatigue forces which arise from typically small but persistent variations in operating conditions. A rotor of

light construction has a low moment of inertia and is better able to withstand the bending moment due to gravity when the blades are horizontal. However it is likely to be prone to buckling under the out-of-plane aerodynamic force. The force of gravity on a rotating blade is also a source of fatigue since the direction of the force reverses with each rotation (Burton et al., 2001, p. 236). A further major source of fatigue is the variation in angle of attack which occurs when the plane of the rotor is not perpendicular to the direction of the wind. All wind turbines rotate in the horizontal plane to bring the rotor to face into the prevailing wind direction, a motion known as yaw. Under real operating conditions, a wind turbine cannot react quickly enough to variations in wind direction to maintain perfect orientation, and therefore experiences variable aerodynamic forces most of the time (Burton et al., 2001, p. 96).

Steel plate has been used in rotor construction in early commercial turbines, but its low strength to weight ratio makes it less than ideal. Most modern turbines use glass fibre, carbon fibre or wood composites. Because of their layered construction, these materials have a relatively high strength to weight ratio and also lend themselves to moulding which again is not possible with steel. Although carbon fibre gives the best performance, fibreglass is usually preferred on cost grounds. Figure 6 shows the typical construction of a fibreglass rotor in cross section showing an internal structural web which helps to provide rigidity and resistance to buckling. Variations on this general design include a larger number of internal webs and variations in shell materials between the leading and trailing edges.

For other turbine components, the choice of materials is more limited. The supporting tower, for example, could be made of steel or concrete, but steel is almost invariably preferred because of the logistical associated with transporting large concrete members (Burton et al., 2001, p.453).

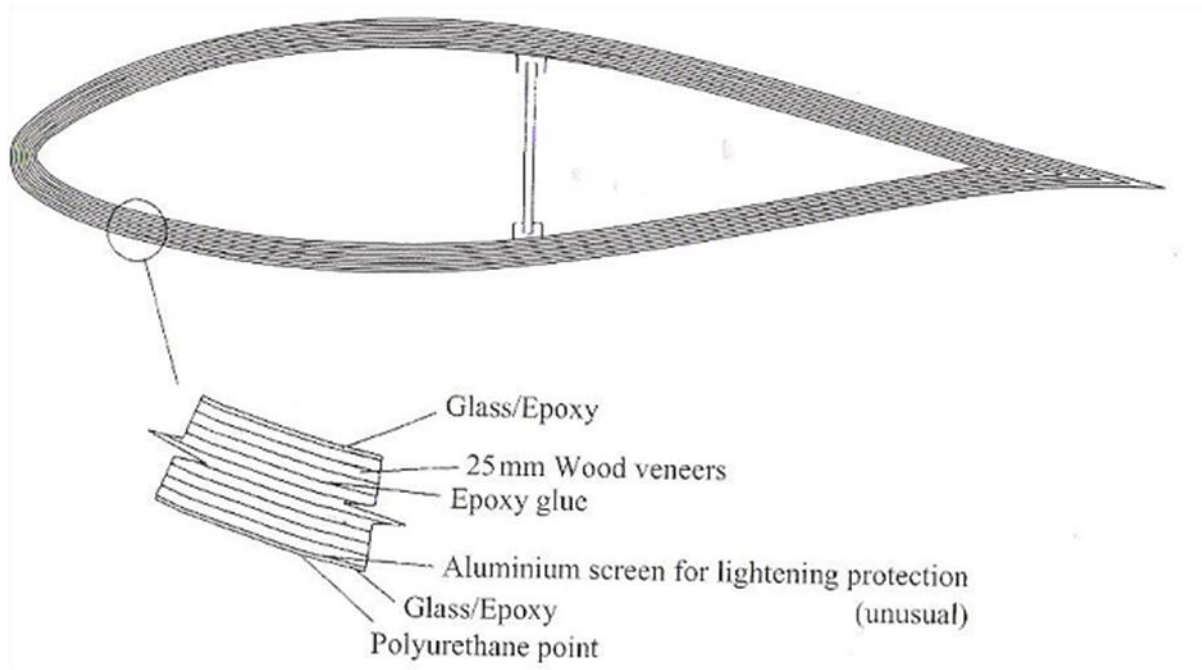


Figure 6: Turbine blade construction (Burton et al., 2001, p. 379)

2.2.4 Mechanical construction

The main mechanical components of a turbine are similar despite the wide range of detailed designs, and are illustrated schematically in Figure 7. The general function of these elements is largely self-explanatory.

The components in Figure 7 make up the turbine drive train which is responsible for transferring the torque produced by the blades to the rotor of an electrical generator. Major design decisions such as the position of the rotor and the speed and control strategies significantly affect the actual arrangement of the elements of the drive train and the need for other mechanical components.

The characteristic shape of the C_P - λ curve for a turbine with a fixed blade pitch (see Figure 2) indicates that maximum efficiency is only achieved at a particular tip speed ratio. By adjusting the pitch angle, however, a turbine can be made to maintain its rated power output at wind speeds higher than rated (Burton et al., 2001, p. 181). Active pitch regulation requires that additional mechanical features to allow each blade to rotate about its own longitudinal axis. This necessarily includes a shaft and bearings for each blade, but the selection of individual or central actuator is a function of detailed turbine design (Burton et al., 2001, p. 351).

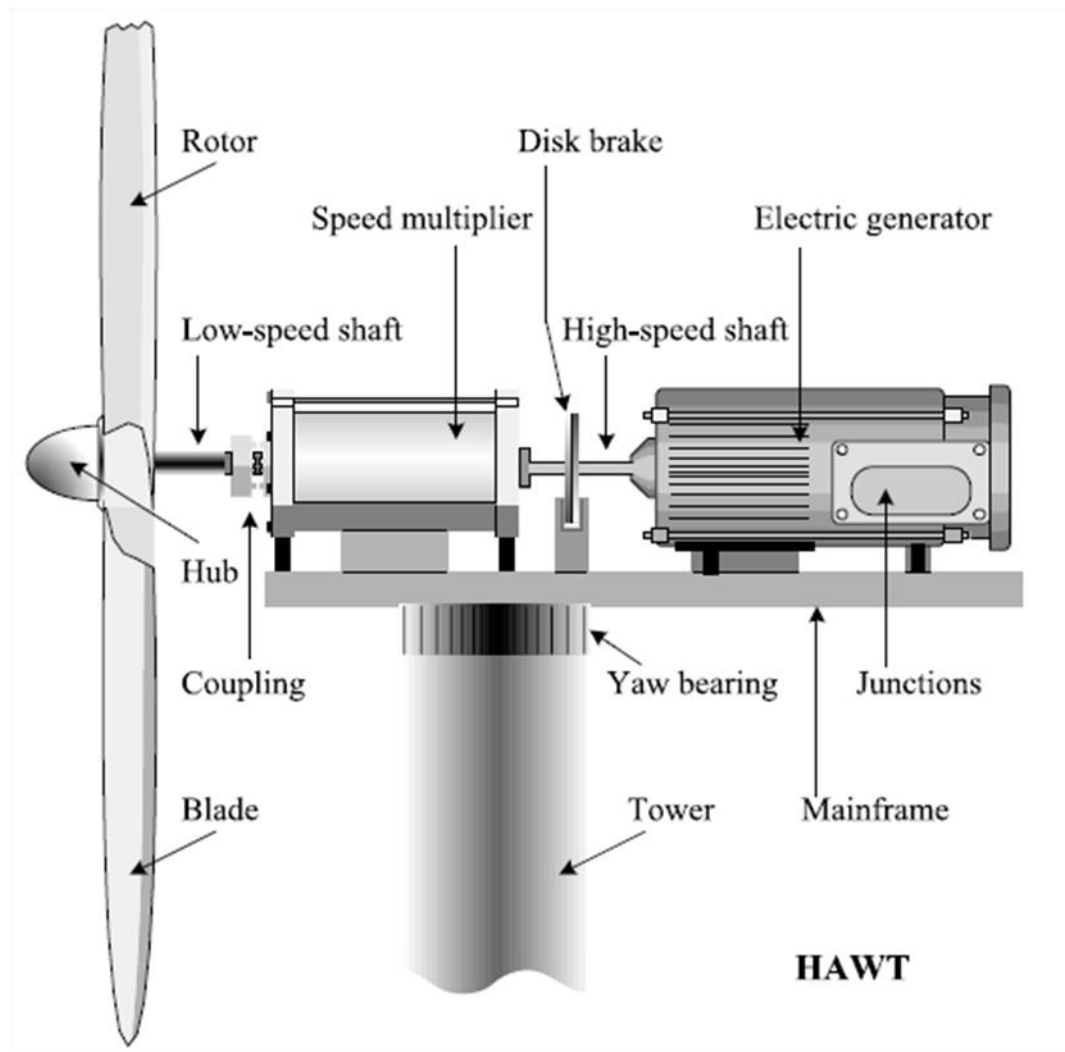


Figure 7: Mechanical construction of horizontal axis wind turbine (Munteanu et al., 2008)

A teeter hinge can also be added to the turbine design in order to limit undesirable loads on blades, low speed shaft, nacelle and yaw mechanism (Burton et al., 2001, p. 347). Most often used on two-bladed turbines, a teeter hinge allows the rotor to pivot by a small amount at the hub. This allows small out-of-plane moments, periodic forces arising from the rotation of the blades and random forces due to turbulent air flow to be absorbed rather than being transferred to the main structural components.

Despite the wide range of mechanical considerations illustrated above, it is the drive train that is of most interest in terms of dynamic behaviour. For larger turbines where blade flexibility is significant, Anaya-Lara et al. (2009) propose a three mass model of the drive train which includes the generator, hub and blades as independent masses connected by torsional springs. However, they derive an effective two-mass

system similar to that presented by Hansen et al. (2003) which is sufficient for most studies. In the two-mass system shown in Figure 8, a large rotating mass representing the rotor is connected to a smaller mass representing the generator via a low-speed shaft, an ideal 1:n gearbox and a high-speed shaft. The moments of inertia of the shafts and gearbox are deemed negligible. Some authors go a step further and represent the turbine as a single-mass system by ignoring the dynamic characteristics of both shafts (Neammanee et al., 2007; Munteanu et al., 2010; Kojabadi and Chang, 2011). In this case, the dynamic behaviour of the turbine can be represented by

$$\frac{Q_{mech}}{n} = \left(\frac{J_{rotor}}{n^2} + J_{generator} \right) \frac{d\omega_{generator}}{dt} + Q_{generator} \quad (4)$$

where Q_{mech} is mechanical torque
 n is the gear ratio
 J_{rotor} is the rotor inertia
 $J_{generator}$ is the generator inertia
 $\omega_{generator}$ is the rotational speed of the generator
 $Q_{generator}$ is the generator torque
(Kojabadi and Chang, 2011)

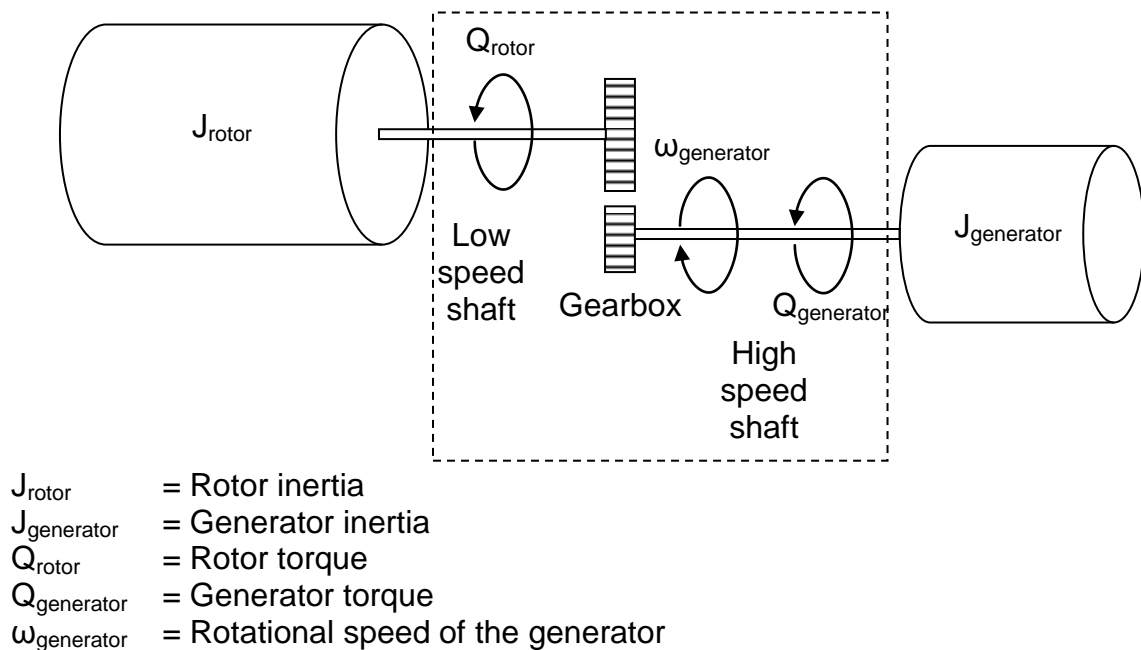


Figure 8: 2-mass model of turbine drive train

2.2.5 Torque oscillations

The majority of large turbines employ a design in which the rotor blades are oriented into the wind in front of the nacelle and tower by an electric motor known as the yaw drive. The alternative arrangement is to place the rotor downwind of the nacelle so that the wind itself maintains the rotor in the ideal position. This passive yaw control makes the yaw drive redundant. The simplicity of the second option means reduced manufacturing cost, reduced maintenance and lower power consumption than the first; however, the downwind arrangement is more susceptible to the phenomenon of tower shadow. The tower presents an obstacle to the flow of air both upwind and downwind and as a rotor blade passes the tower it experiences a momentary drop in air flow. The effect is much weaker in the upwind direction and can generally be ignored in electrical calculations (Chan et al, 1984); however, it must still be taken into consideration in relation to blade loading (Burton et al., 2001, p. 234). In the downwind direction the drop in velocity of the air flow due to tower shadow can be of the order of 20%, and is therefore significant in both cases (Chan et al., 1984).

Tower shadow can be reduced by placing the rotor further from the nacelle, although the effect can still be significant at a distance equivalent to four tower diameters (Burton et al., 2001, p. 373). A lattice tower can be used rather than a tubular one to reduce the effect (Burton et al., 2001, p. 233), although this approach can make the remaining effect dependent on wind direction (Burley et al., 1979 cited by Chan et al., 1984). A number of studies exist that deal with tower shadow in upwind three-bladed turbines (eg. Sørensen et al., 2002; Dolan and Lehn, 2006) and several mathematical models are available of varying complexity; however, the potential flow model used in Garrad Hassan's modelling application, GL BLADED, can equally well be applied to two-bladed machines (Bossanyi and Quarton, 2003). In this model, a 120° sector of the rotor swept area is deemed to be influenced by tower shadow as shown in Figure 9. The wind speed at a point within that zone of influence is given by Eq. 5.

$$V = U \left(1 + \left(\frac{T}{2} \right)^2 \frac{(x^2 - z^2)}{(x^2 + z^2)^2} \right)$$

(5)

where U is the uninterrupted wind speed

T is the tower diameter

x is the lateral displacement of the point from the tower centre line

z is the minimum distance between the plane of the rotor and the centre of the tower

(Bossanyi and Quarton, 2003)

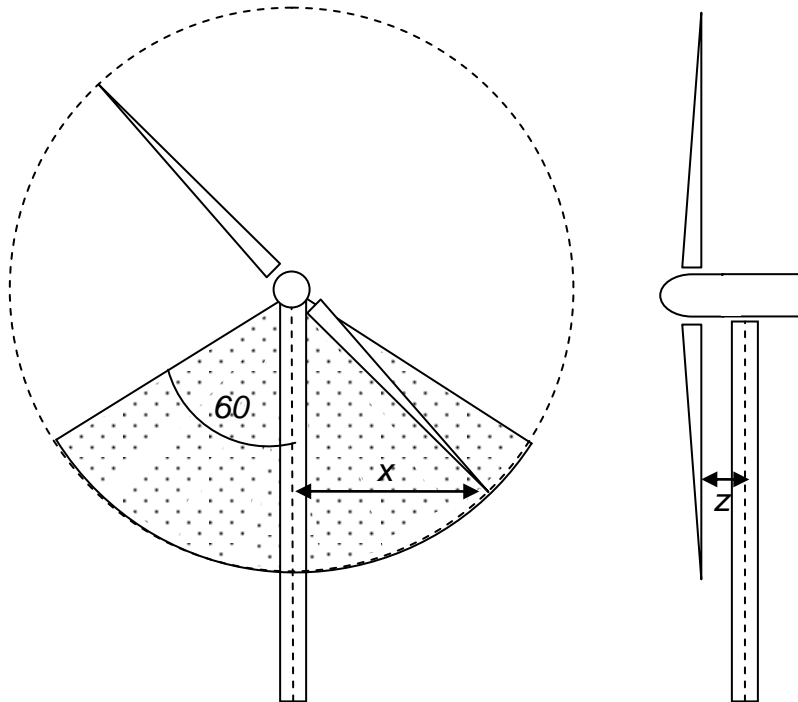


Figure 9: Tower shadow

When a blade is within 60° of top dead centre, it is assumed that $V = U$. For all other rotor positions the factor in brackets in Eq 5 is modified to

$$F(0.5 - \cos(\varphi)) + (0.5 + \cos(\varphi))$$

where F represents the bracketed term in Eq. 5, and φ is the blade azimuthal angle measured from top dead centre of the swept area.

For downwind turbines, the Powles (1983) model which is also used in GH BLADED provides a general solution. The affected zone is the same as for the upwind model as shown in Figure 9, and the wind speed V at a point within the sector is given by Eq 6. For other blade azimuthal angles, the same correction factor is made as for the upwind calculation.

$$V = U \left(1 - \Delta \cos^2 \left(\frac{\pi x}{Wd} \right) \right) \quad (6)$$

where Δ is the maximum velocity deficit directly behind the tower as a fraction of U
 W is the width of the tower shadow as a proportion of the tower diameter d
 (Bossanyi and Quarton, 2003).

Wind shear, whereby wind speeds tend to increase with height above ground level, constitutes a further source of torque oscillation in addition to tower shadow (Burton et al., 2001, p. 233). The result of wind shear is that a rotor blade pointing upwards will experience a higher wind speed than one pointing downwards thus exacerbating the effect due to tower shadow. The problem can be further compounded if the frequency of the resulting oscillation is close to the resonant frequency of either the blades of the tower (Burton et al., 2001, p. 267). Wind shear can be modelled as a logarithmic function given by

$$V_h = V_0 \left(\frac{\log(h/z_0)}{\log(h_0/z_0)} \right) \quad (7)$$

where V_h is wind speed at height h
 V_0 is wind speed at a reference height h_0
 z_0 is the ground roughness length which takes values from Table 2
 (Bossanyi and Quarton, 2003).

Type of terrain	Roughness length z_0 (m)
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Villages, countryside with trees and hedges	0.1
Open farmland, few trees and buildings	0.03
Flat grassy plains	0.01
Flat desert, rough sea	0.001

Table 2: Roughness length values (Burton et al., 2001, p. 19)

2.2.6 Electrical systems

It is clear from Figure 7 that the main electrical element of interest is the generator; however, the type of generator and the requirement for other electrical components depends on the detailed turbine design. Firstly, it is important for later discussions to note that an electric generator is simply an electromechanical machine (EM) used in generating mode (Gross, 2007, p. 79). The same physical device can be used either as a generator where a kinetic input is converted to an electrical output, or as a motor where an electrical input passes through the same circuitry to produce a kinetic output.

Although other energy conversion applications typically rely on synchronous permanent magnet EMs, the natural operation of a wind turbine introduces periodic fluctuations into its output which degrade the power quality. Using an induction generator on the other hand introduces a damping action which reduces the unwanted fluctuations to acceptable levels (Burton et al., 2001, p. 364). Whereas with a permanent magnet EM, the rotor is locked to the rotational speed of the magnetic field in the stator, the rotor of an induction EM rotates at a different speed which varies depending on the electrical and mechanical loads. The difference between the speed of the stator field and the rotor is known as the slip speed and is usually expressed as a percentage of synchronous speed as defined by Eq 8.

$$S = \frac{\omega_s - \omega_r}{\omega_s} \cdot 100 \quad (8)$$

where S is slip
 ω_s is synchronous speed
 ω_r is rotor speed

When slip is positive, the rotor speed is less than that of the stator field and the EM is operating in motoring mode. In contrast, negative slip indicates that the rotor is moving more quickly than the stator field and the EM is therefore in generating mode. The actual relationship between slip and torque for a typical EM is illustrated in Figure 10.

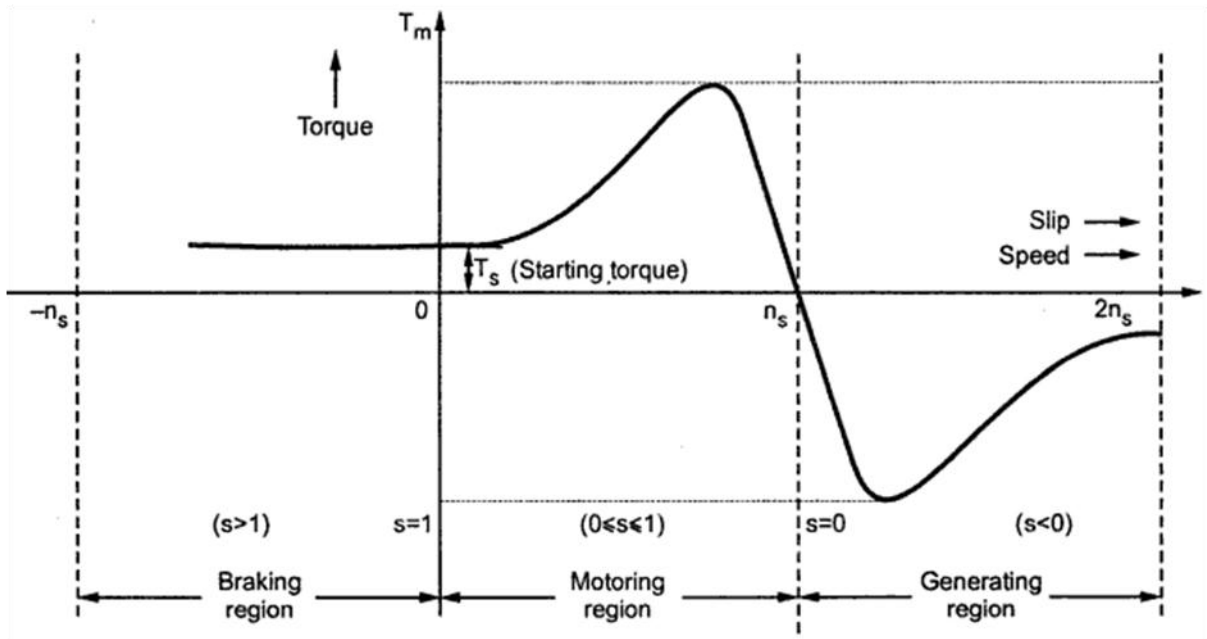


Figure 10: Typical EM torque-speed characteristic (Bakshi and Bakshi, 2009)

The curve is symmetrical about the synchronous speed, n_s , for the region from 0 rpm to $2n_s$. Depending on the design of the EM, operating slip values typically range between 2% and 10% (Gross, 2007, p. 146). Although the torque-speed characteristic of a SCIM can be expressed as an equation, it requires knowledge of certain characteristics of the machine's construction such as the resistance of a single-phase stator winding which must be obtained through measurement.

However, a simpler relationship exists between the torque applied in generating mode, the output power and synchronous speed as shown in Eq. 9.

$$Q = \frac{P}{\omega_s} \quad (9)$$

where Q is torque

P is power

ω_s is synchronous speed

The simplest electrical arrangement for a turbine is for the generator to be directly connected to the distribution network, and in that situation the network frequency determines its rotational speed. This arrangement is very common, and is known either as the Danish model or more descriptively as a fixed speed turbine (Müller et al., 2002). The synchronous speed is given by the formula

$$n_s = 120 \frac{f}{N} \quad (10)$$

where f is the network frequency

N is the number of poles in the EM

(Parekh, 2003).

Thus for a 6-pole EM connected to the UK electricity grid which runs at 50 Hz, the synchronous speed is 1000 rpm. When the torque generated by the blades is sufficient to turn the EM rotor at more than 1000 rpm therefore, the turbine will export power to the network. At lower speeds, the turbine will actually draw power from the network unless it is isolated.

The major disadvantage of the fixed speed design is that the turbine will operate sub-optimally at wind speeds that do not correspond to the peak tip-speed ratio (Burton et al., 2001, p. 360). In order to allow a turbine to operate at variable speed, the generator must be decoupled from the network by interposing a frequency converter; however, this significantly increases the complexity of the design and

hence the cost (Müller et al., 2002). An appropriate frequency converter would be a back-to-back inverter. In this device, an alternating current (AC) of arbitrary frequency is first converted to a direct current (DC) and then into an alternating current which matches the frequency of the network as shown in Figure 11.

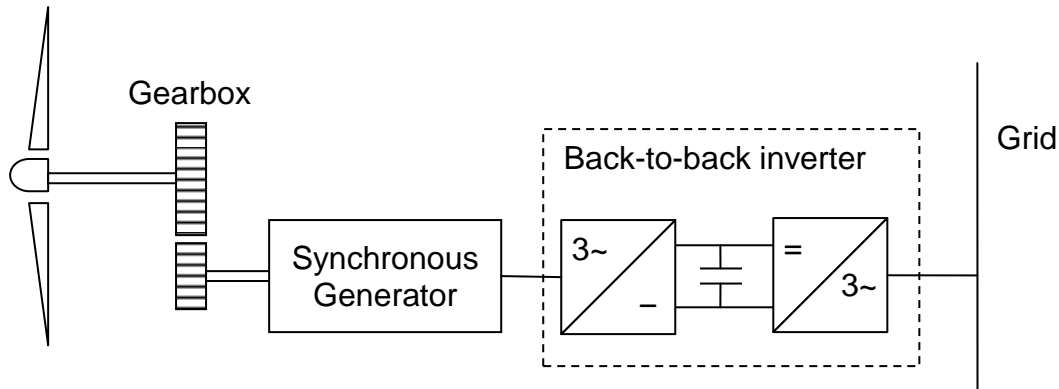


Figure 11: Inline adjustable speed generator (Müller et al., 2002)

With this arrangement any rotational fluctuations in the power output can be smoothed by the frequency converter, and an induction EM is no longer required. However, when the frequency converter is in line with the generator, it has to carry the full power rating of the system which makes it expensive (Müller et al., 2002). An alternative arrangement, shown in Figure 12, is to use a doubly fed induction generator (DFIG). Here the rotor is of the wound construction rather than the simpler squirrel cage design, and is fed with a variable voltage supplied by the frequency converter. Control of the rotor current compensates for variations in speed, and the output can remain at the required frequency. The main advantage over the in-line design is that the frequency converter only needs to carry around 25% of the total system power, and is therefore significantly cheaper (Müller et al., 2002).

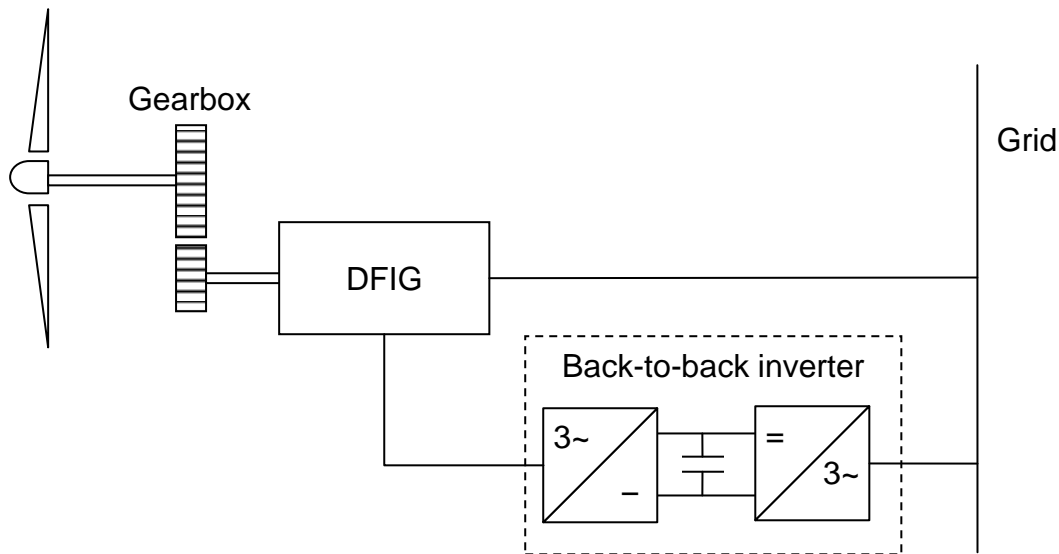


Figure 12: Adjustable speed generator with DFIG (Müller et al., 2002)

As discussed earlier, more complex turbine designs, which include yaw drives or active pitch control for example, require additional electric motors. These are typically fed directly from the distribution network, and do not therefore affect the operation of the drive train components.

2.2.7 Control

The main purpose of control is to ensure that a complex technical process responds in a desired manner to operational changes and external disturbances both to protect the plant and to optimise its operation (Schleicher and Blasinger, 2003; Munteanu et al., 2008, p.). Wind turbine control can be subdivided into three separate categories (Burton et al., 2001, p. 472). The first is supervisory control in which an operator brings the turbine into a particular operating state. The second is closed-loop control in which the adjustment of operating parameters is controlled automatically by a digital controller in response to sensor readings, and the third concerns mechanisms for dealing with potentially dangerous or fault conditions such as excessive tower vibration. Although safety control also depends on sensor readings, it differs from closed loop control in that it typically brings the machine into an exceptional fail-safe state rather than one that is associated with normal operation.

In the context of wind turbine design, it is the external changes in airflow which drive the majority of control actions. Munteanu et al. (2008, p. 5) identify three distinct types of control system in wind turbines:

- Aerodynamic power control
- Generator control
- Grid interface control and power conditioning

Intuitively, the more power a turbine delivers the better. In practice, however, a machine that operates beyond its rated value risks damage to components such as the generator. It is therefore important to limit the power developed at high wind speeds so that safe limits are not exceeded. A simple way to enforce power control is to select a blade geometry which induces a stall condition above a particular wind speed. Referring to the C_P - λ curves in Figure 2, this ensures that the power generated by the turbine declines after a predictable point. This arrangement is known as passive stall control, since it is simply a feature of blade shape (Burton et al., 2001, p.350), and is necessarily only concerned with system protection (Munteanu et al., 2008, p. 26). In contrast, turbines which include the facility to control the pitch angle of the blades can not only avoid potentially dangerous conditions but can also actively optimise the angle of attack for a given prevailing wind speed. This can be done by increasing the angle of attack to induce stall, or by reducing the angle of attack to reduce the aerodynamic lift force, a process known as blade feathering. The additional energy extracted by active pitch control is only about 4% (Burton et al., 2001, p. 351), but allows the turbine to better track the ideal power curve as shown in Figure 13.

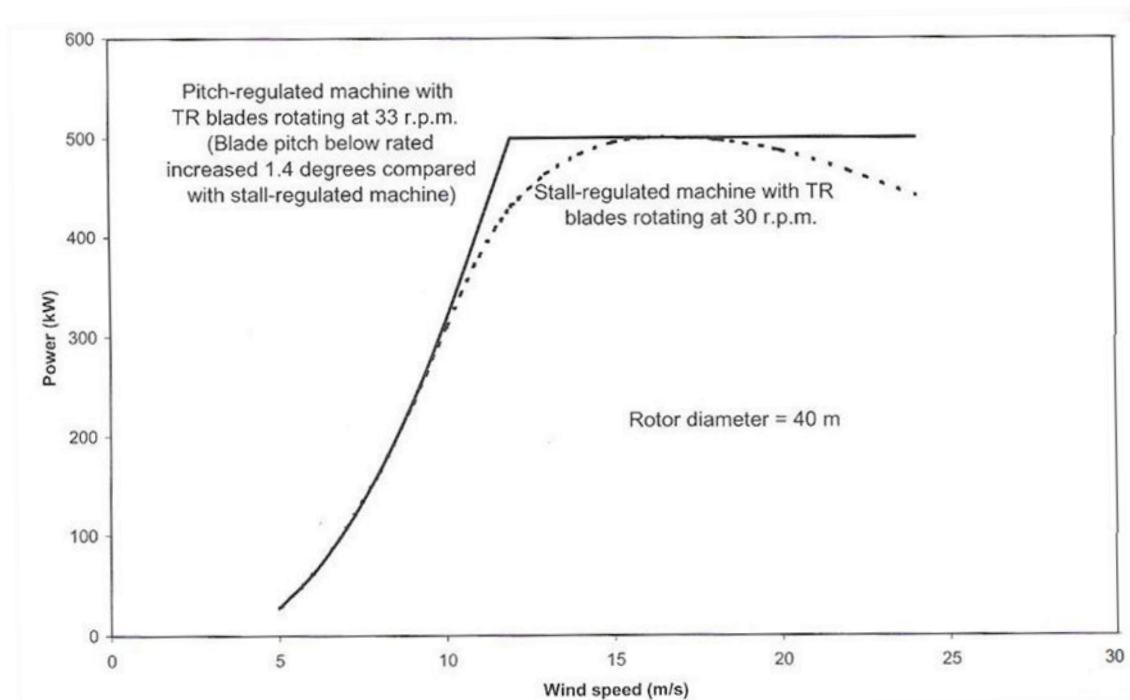


Figure 13: Effect of pitch regulation on performance (Burton et al., 2001, p. 342)

Active manipulation of the aerodynamic behaviour of the blades requires sensors such as anemometers to provide information about prevailing conditions, and digital controllers to select the appropriate settings for blade pitch actuators. This lays the basis for closed-loop control in which operating parameters are adjusted in response to changes in a process variable such as shaft rotation speed to bring the system behaviour closer to a known optimum. The desired value of the process variable is known as the set point, and in the case of wind turbines where external changes account for the majority of adjustments, the set point is determined by reference to a mathematical model of optimum system performance. Closed-loop control is also essential in turbines with yaw drives to maintain the optimum orientation of the rotor plane (Burton et al., 2001, p. 477).

While aerodynamic control is primarily protective, the goal of generator control is concerned with maximising the efficiency of the power conversion. This is most obvious in the case of variable-speed turbines with DFIG generators which provide many opportunities for adjusting operating conditions. For simpler turbine designs with fewer controllable parameters, generator control is still important in order to isolate the turbine from the grid at lower speeds to avoid drawing power.

For smaller turbines, the need for control over their interface with the distribution network is minimal. For larger turbines, however, the quality of their output can affect other devices attached to the network through phenomena such as voltage transients due to wind speed variations, harmonics caused by frequency conversion equipment and periodic fluctuations known as flicker (Burton et al., 2001, p. 580). The requirements for power quality control can be summarised as follows (Sørensen et al., 2005, cited by Munteanu et al., 2008, p. 101).

1. Power/frequency control ability with focus on:
 - a. primary control—fast, automatic adjustment of power to frequency
 - b. secondary control—slower, automatic or manual regulation of the power to the power reference imposed by the system operator at any time.
2. Voltage control ability with focus on voltage regulation and reactive power capability.
3. Dynamic stability with focus on the ability of wind turbines to remain connected to the grid during some specific grid faults.

2.3 Turbine emulation

From the foregoing discussion, it is clear that wind turbines can be very complex pieces of equipment that require complex and expensive components. The industry is also developing very quickly with larger models and new designs frequently being produced. Efficient methods are therefore required for the evaluation of existing design performance and the experimental testing of new designs. Although this is true for most industries, wind turbine designers and manufacturers are also faced with the additional problem that turbines are typically installed in locations that are difficult to access thus making in situ evaluation difficult. Static models of turbine behaviour however cannot capture the real wind regime at a turbine location or the short-term dynamics of drive train components reacting to oscillating torque, resonance and other operational phenomena (Rabelo et al., 2004). This dilemma has led several teams of researchers to propose a range of turbine emulators that can be used to recreate realistic loads on a turbine in a laboratory situation. Different motivations have been invoked including those shown in Table 3.

Motivation	References
Development of control algorithms and techniques	Teodorescu et al., 2003 Chinchilla et al., 2004 Kojabadi et al., 2004 Rabelo et al., 2004 Moore and Ekanayake, 2010 Munteanu et al, 2010b
Analysis of the dynamics of drive train components	Kojabadi et al., 2004 Helsen et al., 2010
Investigation of fault conditions	Mauri et al., 2008 Moore and Ekanayake, 2010
Condition monitoring and fault diagnosis	Yang et al., 2008 Yang et al., 2010 Crabtree, 2011 Johnson and Fleming, 2011
Power quality and network transient analysis	Seman et al., 2005 Mauri et al., 2008

Table 3: Motivations for the use of wind turbine emulators

The basic requirement for a wind turbine emulator (WTE) is that it should reproduce as faithfully as possible the torque generated by a turbine for a particular wind speed (Kojabadi and Chang, 2011). Monfared et al. (2008) summarise required elements of a WTE model as:

- A variable wind speed
- Turbine inertia
- Wind shear and tower shadow
- Steady state characteristics

The specific purpose of the WTE can influence its actual form. For example, because Helsen et al (2010) are primarily concerned with the performance of the gearbox, it is important that their model isolates that particular component and they therefore take a multi-body modelling approach which leads to significant complexity and calculation times. For other purposes, however, the effective two-mass model described by Anaya-Lara et al. (2009) is usually sufficient. With this in mind, the basic structure of a WTE can be derived from the schematic representation of a wind

turbine in Figure 14 where the components inside the dashed boundary are replaced by an alternative source of torque, typically an electrical drive. A computer model of the rotor characteristics provides a reference torque value (Lopes et al., 2005), and a control algorithm ensures that the torque produced corresponds to the reference torque. This arrangement, shown in Figure 15, is ideal for examining the control of the generator and the conditioning of the output power. Because it combines virtual elements with real ones it is often referred to as hardware-in-the-loop (HIL) (Munteanu et al., 2010b) or power hardware-in-the-loop (PHIL) (Ayasun et al., 2007). Strictly speaking, PHIL designates a system in which real power is passed between real and virtual components whereas in a HIL system only information signals are exchanged.

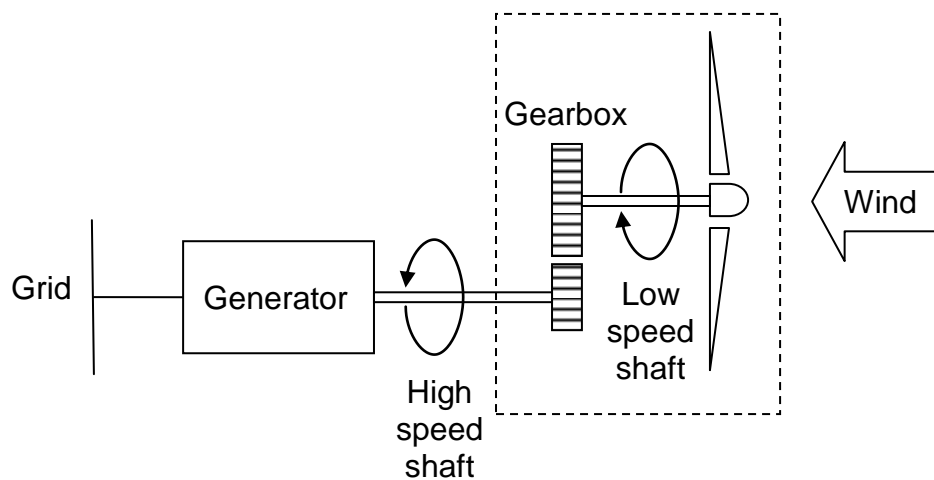


Figure 14: Schematic representation of wind turbine

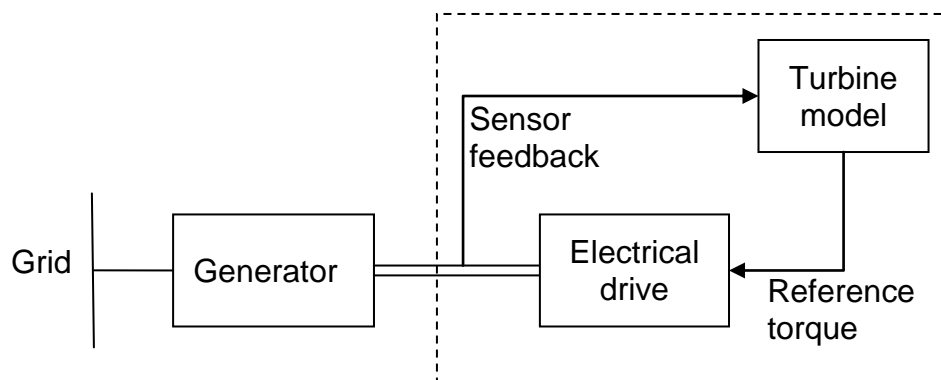


Figure 15: Schematic representation of wind turbine emulator

Clearly, the schematic in Figure 15 represents a very general model of a WTE, and additional hardware components would be required to emulate more complex designs which include, say, a DFIG generator. Likewise, an appropriate computer model would be required for the particular turbine design being emulated. It is also worth noting that given an appropriate model of the prime mover, the arrangement shown is not restricted to wind turbine emulation, and could equally well be applied to other forms of electricity generation. This generic approach is the one taken by Mauri et al. (2008) and Munteanu et al. (2010).

A distinction can be made between the set of physical WTE components and those that replace elements of the real environment such as the prime mover. Testing usually focuses on the behaviour of the former, which in PHIL terms is designated the hardware under test (HUT).

2.3.1 Drive selection

Several teams of researchers have suggested using a DC electric motor as an alternative source of torque in a WTE (Chinchilla et al., 2004; Lopes et al., 2005; Monfared et al., 2007; Weiwei Li et al., 2007; Mauri et al., 2008; Martinez et al., 2009; Moore and Ekanayake, 2010; Munteanu et al., 2010, 2010b; Crabtree, 2011). The attraction of a DC machine is that the torque it produces is directly proportional to the armature current, and is therefore very easy to control (Lopes et al., 2005). In fact, Martinez et al. (2009) propose a WTE for fixed pitch turbines which consists of nothing more than a DC motor connected in series with a resistance and a variable voltage source. However, no detailed evaluation is presented, and the main justification for the design is that the power curve of the DC motor is roughly the same as that of a fixed pitch turbine.

Permanent magnet synchronous machines (PMSM) have also been proposed for use in WTEs (Dolan et al., 2005; Weihao Hu et al., 2008). The main benefits of a PMSM are that it offers higher impulse torque and power density and faster speed of response in comparison to a DC machine (Dolan et al., 2005). Because it does not require an excitation system, the PMSM also has the advantage that there are no associated field losses (Gross, 2007); however, torque control is more difficult because its relationship with the three-phase sinusoidal current is complex. Using a mathematical operation known as Park's Transform, the three AC phase currents

can be reduced to two DC components in a rotating frame of reference (Lee et al., 1984). In the rotating frame of reference, a direct current component (d) rotates at a 90° phase angle from a quadrature component (q). The torque in the PMSM can be shown to be proportional to the quadrature current (Pillay and Krishnan, 1988). Once the required current in the q-axis has been calculated, the equivalent AC supply to the PMSM can be found by applying the inverse Park transformation. This method for controlling a PMSM is known as field-oriented control (FOC) and can be accomplished relatively easily using a microprocessor (Gabriel et al., 1980).

A third group of WTE studies use a squirrel-cage induction machine (SCIM) to provide the required torque, usually citing the SCIM's rugged design and lower cost as benefits (Teodorescu et al., 2003; Kojabadi and Chang, 2004; Ming Qiao et al., 2007; Neammanee et al., 2007; de Oliveira et al., 2007; Yaoqin Jia et al., 2007). The torque produced by a SCIM can be controlled using FOC in the same manner as for a PMSM. As a consequence of choosing this type of drive, a reliable variable voltage source is also required and Kojabadi and Chang (2004) propose an inverter based on insulated gate bipolar transistors (IGBT). This type of inverter is typically composed of two main components as shown in Figure 16. The rectifier converts the standard AC supply to DC, and the inverter component whose basic structure is shown in Figure 17 uses a set of IGBTs under microprocessor control to produce a series of pulses in three phases. The resulting output in each phase uses pulse width modulation (PWM) to synthesise a sinusoidal voltage of the required frequency as shown in Figure 18. The inverter therefore converts the problem of frequency and voltage magnitude control into one of IGBT switch timing (Gross, 2007).

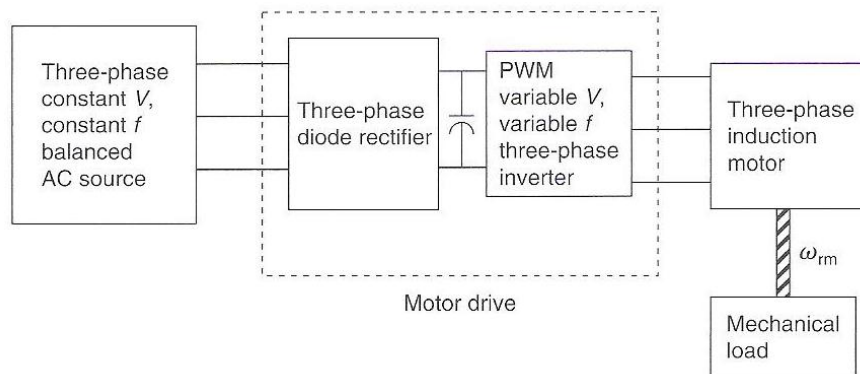


Figure 16: General configuration of PWM motor drive (Gross, 2007)

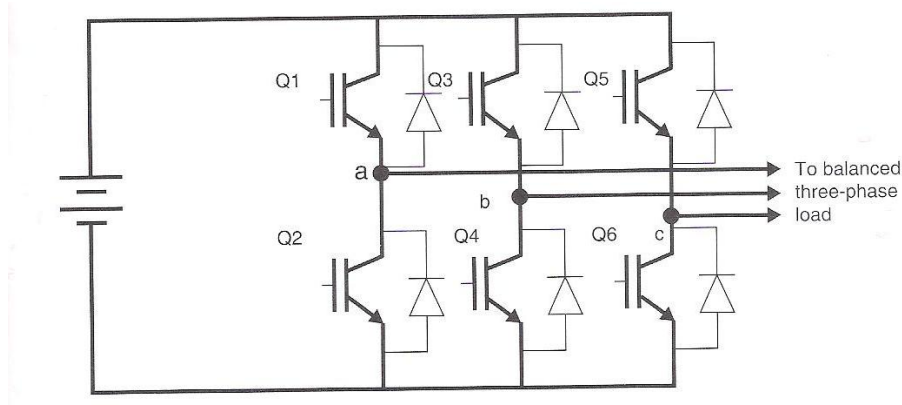


Figure 17: The three-phase IGBT circuit diagram (Gross, 2007)

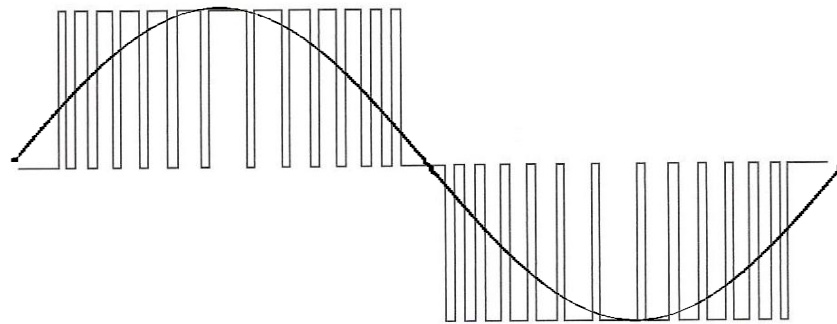


Figure 18: Approximation of a sine wave using PWM (Adapted from Gross, 2007)

2.3.2 Turbine model

The purpose of the turbine model is to provide a reference torque for the WTE drive. It therefore consists of a static element which describes the torque produced by the rotor as a function of wind speed using Eq. 3 and a dynamic element that describes the torque oscillations produced by wind shear and tower shadow using Eq. 7 and either Eq. 5 or Eq. 6. The static element requires an understanding of the turbine's performance at different wind speeds. As noted by Teodorescu et al. (2003), the distribution of torque coefficient with tip speed ratio is more useful in this case than the power coefficient. The torque-speed characteristic can be obtained from test data where available, or derived from the turbine manufacturer's published data. Yaoqin Jia et al. (2007), for example, provide a procedure for deriving C_Q from the parameters shown in Table 4.

Symbol	Quantity
R	Rotor radius (m)
J	Inertia (kg/m ³)
PW	Rated power (kW)
ωW	Rated rotating speed (rpm)
VW	Rated wind speed (m/s)
ωM	Maximum rotating speed (rpm)
VS	Startup wind speed (m/s)
VIN	Cut-in wind speed (m/s)
VOUT	Cut-out wind speed (m/s)
TS	Startup torque (Nm)

Table 4: Wind turbine parameters (Yaoqin Jia et al., 2007)

To compensate for the difference in inertia between the rotor and the electrical drive, Kojabadi and Chang (2011) develop Eq. 11 based on Eq. 4 above. Given a description of the mechanical torque, the only additional piece of information required is the generator shaft speed as noted by Lopes et al. (2005).

$$Q_{drive} = \frac{Q_{mech}}{n} + \left(J_{drive} - \frac{J_{rotor}}{n^2} \right) \frac{d\omega_{generator}}{dt} \quad (11)$$

where Q_{drive} is the torque required from the electric drive

J_{drive} is the inertia of the electric drive

Q_{mech} is mechanical torque

n is the gear ratio

J_{rotor} is the rotor inertia

$\omega_{generator}$ is the rotational speed of the generator

(Monfared et al., 2008; Kojabadi and Chang, 2011).

The torque output of the WTE drive needs to be controlled to the reference value provided by Eq. 11 in order to produce a realistic result.

2.3.3 Instrumentation and control

Knowing the torque produced by the WTE is clearly important if it is to be controlled with reference to the turbine model. There are essentially three options, the first of

which is to estimate the torque based on known characteristics of the drive. This is the approach taken for example by Martinez et al. (2009), Ming Qiao et al. (2007) and Monfared et al. (2008). Details of the process for estimating the drive torque are not provided; however, Monfared et al. include a component in their reference torque calculation aimed at compensating for the inertia of the drive itself. This was a problem identified by Dolan et al. (2005) as one of the reasons for including a torque transducer.

The second option is to take direct measurements from the WTE drive and calculate the torque. This is easier in the case of a DC-based WTE because of the direct relationship between torque and current. Moore and Ekanayake (2010) and Munteanu et al. (2010), for example, calculate torque in this way. Neammanee et al. (2007) on the other hand use a SCIM in their WTE, and use the speed of the generator shaft as a surrogate for torque. Exactly how this is done is not explored in the paper. De Oliveira et al. (2007) who also use a SCIM rely in contrast on the relationship between torque and slip illustrated in Figure 10.

Finally, torque can be measured directly using a torque transducer¹. Crabtree (2011) takes this approach and also collects a wide range of other sensor readings because of his interest in fault diagnosis. Dolan et al. (2005) also measure torque directly as mentioned earlier in order to compensate for motor inertia.

Only extremely simple WTEs in the literature rely on open-loop control (Martinez et al., 2009). All others implement a form of closed-loop control in which the torque delivered by the emulator is compared to the reference torque value supplied by the turbine model as shown in Figure 19. Note that the diagram shows the rotational speed of the drive/generator shaft being used to calculate actual torque using the relationship between torque and slip. This element could equally well be replaced by a torque transducer to measure torque directly.

¹ See for example <http://www.datum-electronics.co.uk/how-to-measure-torque.aspx>

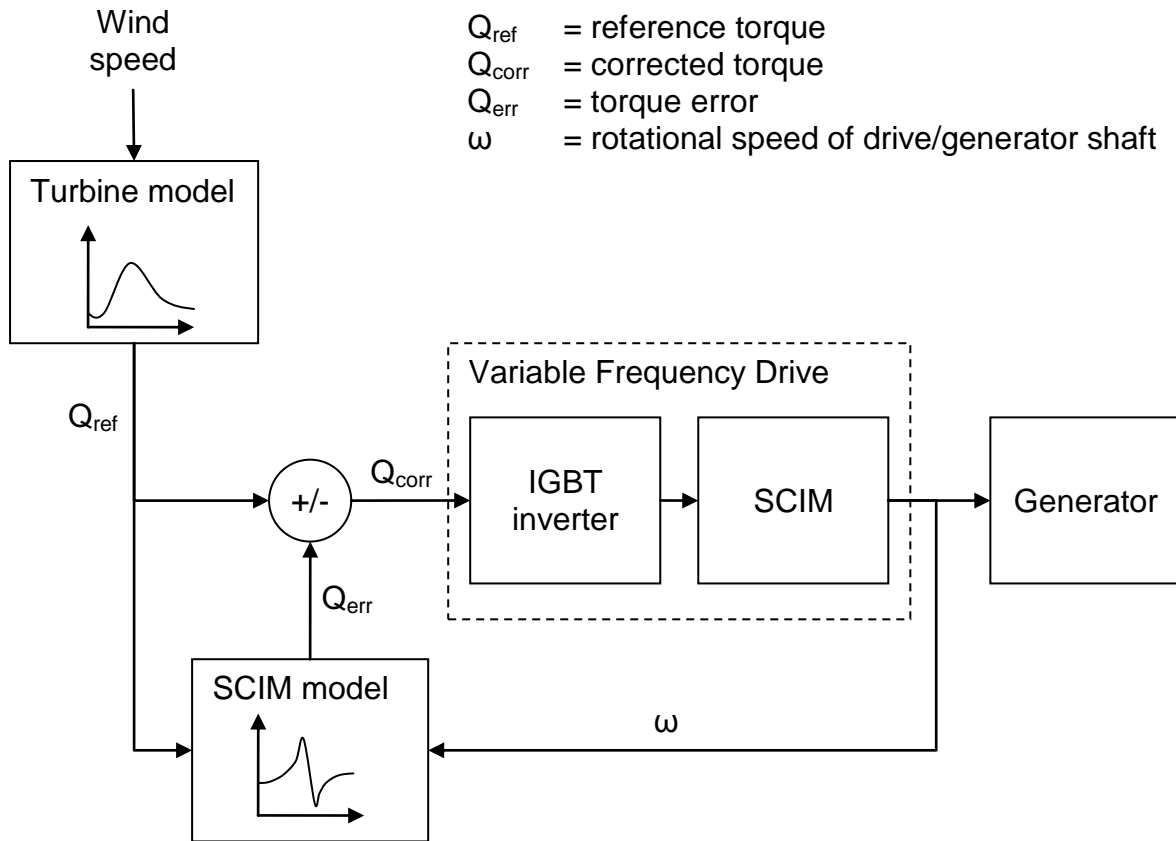


Figure 19: Block diagram for WTE torque control

2.3.4 Input data

The final element required for a WTE is a source of wind speed data. The three main options here are

- Directly-controlled wind speeds
- Artificially generated time sequence
- Logged time sequence

The choice of input type is determined by the type of test being conducted. Many research teams use the first option because it facilitates the observation of system behaviour under controlled conditions (Bouscayrol et al., 2005; Hsu Wen-Ko, 2010; Kojabadi et al., 2004; Lopes et al., 2003; Mansouri et al., 2003; Munteanu et al., 2010b; de Oliveira et al., (2007); Seman et al., 2006; Teodorescu et al., 2003; Weihao Hu et al., 2008; Weiwei Li et al., 2007). Direct control over wind speed

allows for steady state observations, step changes in wind speed and steadily ramped speed changes.

Where testing is focussed on aspects of turbine operation with a strong stochastic element such as fault diagnosis or the characterisation of effects due to turbulence, time series data is preferred. In these situations, wind models such as those described by Diop et al. (2007) can be used to generate synthetic time series, or real logged data can be used (Chinchilla et al., 2004). Examples of both approaches are found with Crabtree (2011) preferring synthetic data and Dolan et al. (2005) opting for logged data. Monfared et al. (2007) and Yaoqin Jia et al. (2007) use time series data but do not specify the type, and Neannamee et al. (2007) use all three types of input signal because of their interest in testing the capabilities of their WTE.

2.4 Conclusion

This chapter reviews the essential aspects of wind turbine design that are needed to specify and construct a WTE. As noted in §2.3, the specific design of a WTE necessarily follows from its purpose and the type of tests that it is intended to support. Each topic covered here could therefore be explored in much greater detail with respect to a specific WTE. That was not the purpose of the review, however, and a broad background was intended.

Chapter 2 reviews, compares and summarises previous work on WTE design, construction and evaluation, and presents a general model for a WTE. This will be used to underpin the rest of this report.

3 Methodology

3.1 Introduction

The purpose of this chapter is to describe the methods used during the completion of the project. The following sections cover the main stages of the project process in chronological order.

3.2 Project selection

An initial set of parameters was defined for the project which provided a context for the selection of the actual project. Each criterion was personally motivated, and the list can be summarised as follows:

- Focus on control engineering applied to renewable energy technology
- A highly practical element
- Collaboration with an industrial partner
- Sufficiently short timescale to allow completion within by the August 2011 deadline

No one particular energy technology was deemed more attractive than another for the purposes of project selection in order to increase the range of potential opportunities. The chart in Figure 20 describes the subsequent three-stage process that was undertaken to arrive at a final project decision.

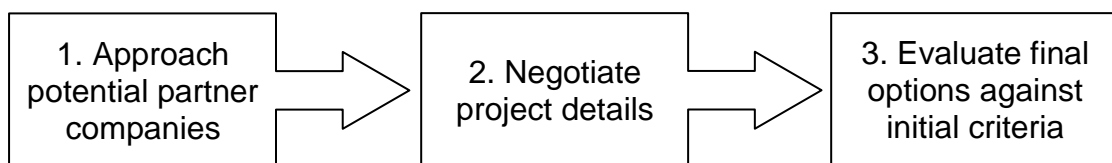


Figure 20: Project selection process

Scottish Renewables maintains a membership directory with company contact details which is accessible on their Web site². Currently there are just over 300 companies listed. During the week beginning 18th April 2011, all entries in the list were examined to filter out unlikely partner organisations such as local authorities,

² <http://www.scottishrenewables.com/members/membership-directory/>

legal firms, consultancies, etc. The result was a shortlist of 31 companies who were mainly small and locally based to facilitate communications during the project. Some larger companies were also included if they had known interests in the Edinburgh area. The list also contained a small number of research centres in addition to commercial firms.

All shortlist members were contacted on 22nd April 2011 by email using a variation of the text in Appendix A and a CV was included as an attachment. Between 22nd April and 31st May, 11 replies were received, out of which 5 were polite refusals. This left 6 possibilities.

Negotiations were undertaken by email, telephone and face to face until a final decision was made on 9th June 2011 to select the current project in cooperation with Gaia Wind Ltd. This decision was taken slightly later than anticipated, but the negotiation period allowed a clear project brief to be developed which is provided in Appendix B. Prior to the final project selection, two alternative project proposals were lodged with the dissertation Module Leader, one related to the Gaia Wind project, and another as a backup which did not rely on any external collaboration. This was a contingency in case of problems during the negotiation process. The two initial proposals can be found in Appendix C along with a second version of the Gaia Wind document which was the result of scoping discussions with the company.

3.3 Literature review

Early literature searching focussed on previous examples of WTE projects. Science Direct and Google Scholar were the most useful search tools, and a large number of sources were found spanning the period 2003 – 2011. Given the abundance of examples, a representative set was selected that covered the indicated time period, but which concentrated for the most part on more recent work.

It was clear from the outset that some theoretical subjects needed to be included in the literature review. The University library catalogue was used to identify appropriate textbooks for this purpose, hence the reliance on Burton et al. (2001) for much of the background on wind turbine technology. This particular choice was justified by the frequent references to Burton et al. in the research literature.

Further reference material was identified during the literature search and review process by following up references in the papers themselves. This led to the identification of several authors who filled important gaps in the background.

Two main approaches were taken to organise the identified references. The first was to make paper copies of those papers relating to WTE studies and to highlight important passages. These were later copied into an early draft of the literature review so that they could be incorporated into the text at the appropriate points. The second approach was to collect electronic copies of all available references onto a PC. This facilitated fast electronic search within the documents.

When setting out the structure of the literature review, the outline view in Microsoft Word was used to develop short notes which were developed into complete sections as a second stage.

3.4 Project scope

The overall aim of the development was to create a general purpose WTE which could be used to recreate arbitrary wind conditions to test the response of the Gaia Wind turbine controller. However, it was agreed that this would not be possible within the time constraints on the project. The WTE development was therefore split into two phases of which this project is the first with the general aim of establishing communications with the VFD and turbine controller via a PC-based human machine interface (HMI). Thus the initial system will not include a turbine model. Instead of wind speed as input, a target speed of rotation will be specified by the user. This is sufficient to satisfy the immediate requirement of the company for a means for performing benchmark tests. The introduction of the turbine model, the provision of wind speed data as input and closed-loop torque control are therefore deferred to the second phase. The following sections discuss the specific objectives related to the aim of the first phase project.

3.4.1 Evaluate hardware setup

Gaia Wind has already put in place the hardware for a WTE. The adequacy of this setup needs to be evaluated with respect to the requirements discussed in the literature review. This evaluation will set the limits on what is possible with the current configuration, and suggest ways that the hardware setup could be improved.

3.4.2 Establish communication with VFD

The VFD, of which a Weg CFW-11 IGBT inverter is the main component, provides a range of control opportunities via its programmable parameters. To achieve this objective, those opportunities need to be identified, a suitable method of communication needs to be selected, and the communication management software needs to be written. Part of the brief from the company is that this should take the form of an identifiable module within the overall software development.

3.4.3 Establish communications with turbine controller

The existing turbine controller is supplied by Danish company Mita Teknik, and provides information on a range of operational parameters. The achievement of this objective will depend on developing a familiarity with the communication protocol implemented by the controller, and writing the communication management software. Again, the company brief specifies that this should be an identifiable module within the overall software application.

3.4.4 Construct HMI

The company brief specifies that the HMI should take the form of a PC application written in Microsoft Visual C#. The basic requirement is therefore to develop an interface which provides a means to control the hardware as specified and to log performance data during a test run which includes generator efficiency and generator slip. This implies integration with both communications modules, and some basic calculations based on the data that they supply. The company brief can be found in Appendix B and the final functional specification in Appendix K.

The appropriateness of the selected development tools is also considered.

3.4.5 Evaluate results

The initial development is quite simple in comparison to the WTE projects covered in the literature review. The evaluation therefore consists mainly in verifying that the HMI is operating as specified. However, the data available from the system provides a means for evaluating the reliability of the values delivered by the inverter and controller interfaces.

3.5 Timescale

The initial project plan can be found in Appendix D. The overall duration was already fixed as discussed previously given the target deadline of August 25th. During negotiations with Gaia Wind, it became apparent that it would be advantageous to have access to the hardware during the main software development period and that an intense period on site at the company premises in Glasgow would be necessary. A mutually convenient period of three weeks was identified from 27th June – 15th July 2011. This essentially split the project into three phases as described in Table 5. The gap in the timeline from 16th – 28th July was due to a holiday.

Phase	Activities	Dates
1	Literature review Familiarisation with Visual C# and Microsoft Visual Studio Initial work with equipment manuals First draft of system design	10th June – 26th June
2	Detailed familiarisation with hardware Software development	27th June – 15th July
3	Evaluation Write-up	29th July – 25th August

Table 5: Overall project structure and schedule

3.6 Investigation of hardware configuration

The hardware for the WTE had already been assembled by Gaia Wind. It was therefore important to become familiar with the components that were already in place. The central component was the Weg CFW-11 IGBT inverter (Weg, 2008) and familiarisation largely consisted of working systematically through the programming manual to identify the relevant operational parameters that would need to be manipulated. The detailed results of this work can be found in the *Inverter Communications* section of the system specification document in Appendix K.

The other main pieces of equipment that were included in the investigation were the turbine itself and the Weg SCIM generator whose datasheet can be found in Appendix E. Turbine details were obtained from test documentation from the United States National Renewable Energy Laboratory (NREL) relating to the Gaia Wind turbine (NREL, 2009), and from various Gaia Wind publications (Gaia Wind, 2008, 2009, 2009b).

The familiarisation phase did not really have a defined end, since new and revised information was identified throughout the development period.

3.7 Software development

The requirements for the system were reasonably clear from the outset, a first draft of the system specification having been sent to Gaia Wind on 23rd June. The development approach adopted was an agile one³ in which the features of the system were prioritised so that less important details could be omitted if delays occurred.

A further feature of agile development is the regular delivery of prototypes. Three main prototypes were envisaged corresponding to the three main modules of the system. The initial intention was to complete the inverter interface first, followed by the turbine controller interface and then the HMI. This is shown in the project plan in Appendix D. In fact, at the beginning of the development period, the plan had to be changed because the hardware was in use for other purposes. Consequently, a top-down approach was taken and the HMI was addressed first, followed by the inverter interface and the turbine controller interface.

In general, the development plan was successful, and a main prototype was completed at the end of each of the three weeks.

Regular backups were taken throughout the development period.

Because of the agile approach, the system specification was continually updated throughout the development period to reflect the evolving design. The final version can be found in Appendix K.

3.8 System design

Conceptually, the software system consists of four main components as shown in Figure 21. Two interfaces are provided, one to the VFD via the Weg inverter, and another to the controller of the turbine under test. The operation of these pieces of equipment are summarised in §4.1. The test management module concerns the construction and operation of scripted tests, while the HMI provides the means for

³ See for example http://en.wikipedia.org/wiki/Agile_software_development

the user to control the VFD, to monitor the response of the turbine generator, and to perform the summary calculations based on the information from both units.

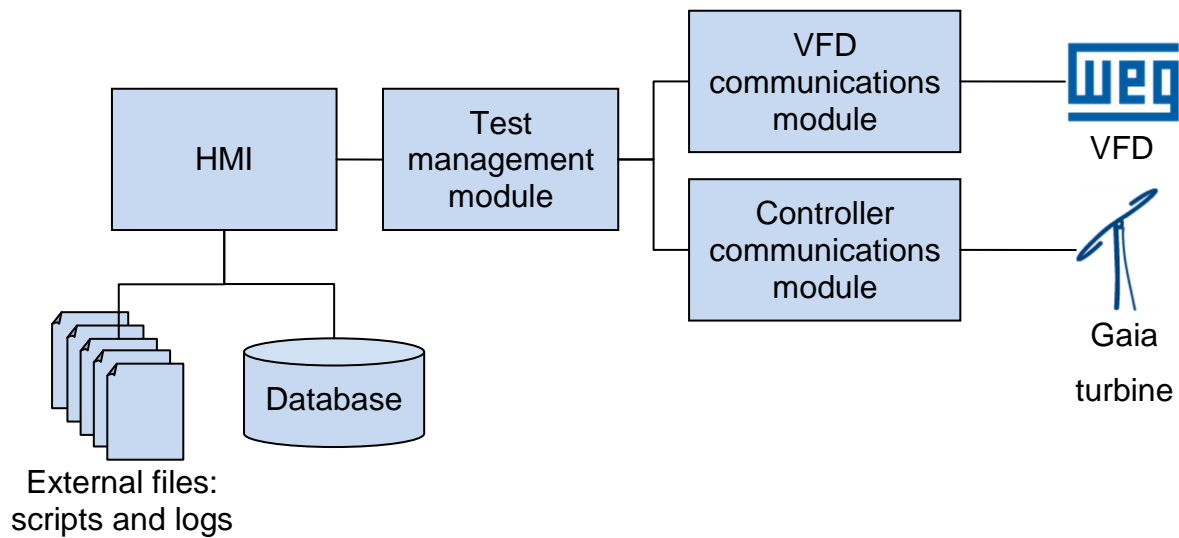


Figure 21: High-level system design

The HMI allows the user to specify the speed of the VFD, which is theoretically the same as the angular velocity of the generator rotor. Input can be specified directly, or as part of a scripted series of speeds with associated durations.

Among other quantities, the VFD interface provides the following information about the input to the WTE:

- Angular velocity of the drive rotor
- Electrical power
- Drive torque

The controller reports the electrical power output from the turbine generator, and given the appropriate version of the controller firmware, also report the angular velocity of the generator rotor.

Based on the data from the two interfaces, the HMI provides calculated figures for the generator slip and overall efficiency. Slip is calculated from the speed of the generator and the network synchronous speed of 1000 rpm, while the efficiency figure is based on the input power and output power reported by the inverter and turbine controller respectively.

The company brief (Appendix B) specifies the ability to log operational data from a test run to an external file. The inclusion of this feature makes the generation of test data a simple process. The software automatically logs the following data to an Excel file at a location specified by the user which can then be used in the evaluation as explained in the next section:

- Timestamp
- Drive rpm
- Drive power
- Generator rpm
- Generator power
- Efficiency (%)
- Slip (%)

The full software system specification can be found in Appendix K.

3.9 Evaluation of results

The correct operation of the software compared to the specification can be verified through observation. As with any piece of software, it is to be expected that unforeseen errors will be identified at various stages through the development and after delivery. However, these are of less importance to the current project than the physical operation of the WTE itself, and the accuracy of the information provided by the HMI. The goals of the evaluation are therefore to answer the following questions:

- Is the behaviour of the HUT comparable to that of a real installation?
- Can the efficiency of the HUT be disaggregated from that of the other WTE components?
- What variation is evident in the performance of the WTE?

3.9.1 Comparison with real installation

In 2009 and 2010, NREL carried out a series of tests on the Gaia Wind turbine according to the International Electrotechnical Commission (IEC) standards. The reports are now published and constitute a reliable description of the operation of a real turbine. The most relevant report is the result of the power performance test (Huskey et al., 2009) which includes binned wind speed data with corresponding

instantaneous power and power coefficient. Unfortunately, there are significant differences between the NREL installation and the WTE. The primary reason is that the American distribution grid runs at 60 Hz while in Europe the grid frequency is 50 Hz. This means that the synchronous speed of a 6-pole SCIM is different, and therefore a different model of generator is used in the American version. A further consequence of the different rotational speeds is that a different gear ratio is required.

Because the current version of the Gaia WTE does not include a turbine model, a direct comparison with the NREL data is not possible; however, had the grid frequency not been different, the torque-speed characteristics of the generators in each case could have been compared to identify any divergences in behaviour. Unfortunately, this exercise would have little validity given the differences in the two cases. Using the NREL data for comparison was therefore abandoned; however, in exploring ways of using that data, some interesting observations were made and these are provided in Appendix H. No other dataset for the European version of the turbine was available at the time of writing, and therefore a comparison with a real installation was not feasible.

3.9.2 WTE efficiency

The HMI provides a calculated efficiency value η based on the relationship between the power output by the generator and the power delivered by the VFD according to Eq. 12.

$$\eta = \frac{P_{out}}{P_{in}} \quad (12)$$

Some power loss is associated with each energy conversion step in the WTE, which means that the overall efficiency is the product of the individual efficiencies of the components. This is expressed in Eq. 13.

$$\eta = \eta_d \cdot \eta_{dgb} \cdot \eta_{ggb} \cdot \eta_g \cdot \eta_u \quad (13)$$

where

η_d = drive efficiency
 η_{dgb} = drive gearbox efficiency
 η_{ggb} = generator gearbox efficiency
 η_g = generator efficiency
 η_u = factor for unknown losses

The datasheet for the SCIM (Appendix E) provides values for efficiency at different percentage loads. Manually controlling the load to match the values provided reduces the theoretical uncertainty in the value of the SCIM efficiencies, and any remaining inefficiency can be attributed to the other components. Knowledge of the losses attributable to the WTE setup itself can be useful in interpreting the performance of the HUT.

The procedure for this test is to set the percentage load on the generator manually to 50%, 75% and 100% of rated using the power value from the turbine controller. The WTE is run for 10s at each speed and the calculated efficiency values are logged every second. The efficiency of the balance of system components (gearboxes, drive and unknowns) is found by dividing by the quoted efficiency for the generator at these standard loads.

3.9.3 Duration test

The variation in performance of the WTE can be assessed by collecting data over a range of speeds and creating a box plot of each of the logged quantities. This will provide a performance envelope that defines the accuracy of the values currently displayed by the HMI.

For this test, the generator speed is raised just above synchronous speed and held long enough for the turbine controller to close the grid connection. Thereafter, the inverter reference speed is incremented by 1 rpm from 1005 to 1020 rpm. Each speed setting is maintained for 30s and the speed reading from the turbine controller is logged every second.

4 Results

This section summarises the output from the activities described in §3.4.

4.1 Hardware configuration

The sections below summarise the important characteristics of the individual components of the WTE, and the overall construction.

4.1.1 Overview

The Gaia Wind turbine is a two-bladed, fixed pitch, fixed speed unit which is designed according to the Danish model. Its principal design parameters are summarised in Table 6. Where two values are given, the first corresponds to the European version of the turbine which is designed to be connected to a 50Hz distribution network, and the second refer to the American version designed for a 60Hz network.

Characteristic	Value
Rotor diameter	13 m
Rotor weight	200 kg
Hub height	18.3 m
Rated electrical power	11 kW
Rated wind speed	9.5 m/s
Start-up speed	2.5 m/s
Cut-in wind speed	3.5 m/s
Cut-out wind speed	25 m/s
Gear ratio	18:1 / 21.6:1

Table 6: Main characteristics of the Gaia Wind 11kW turbine (Gaia Wind, 2009)

The overall turbine design shown in Figure 22 is relatively simple and provides no opportunity to alter the aerodynamic properties of the rotor via pitch control.

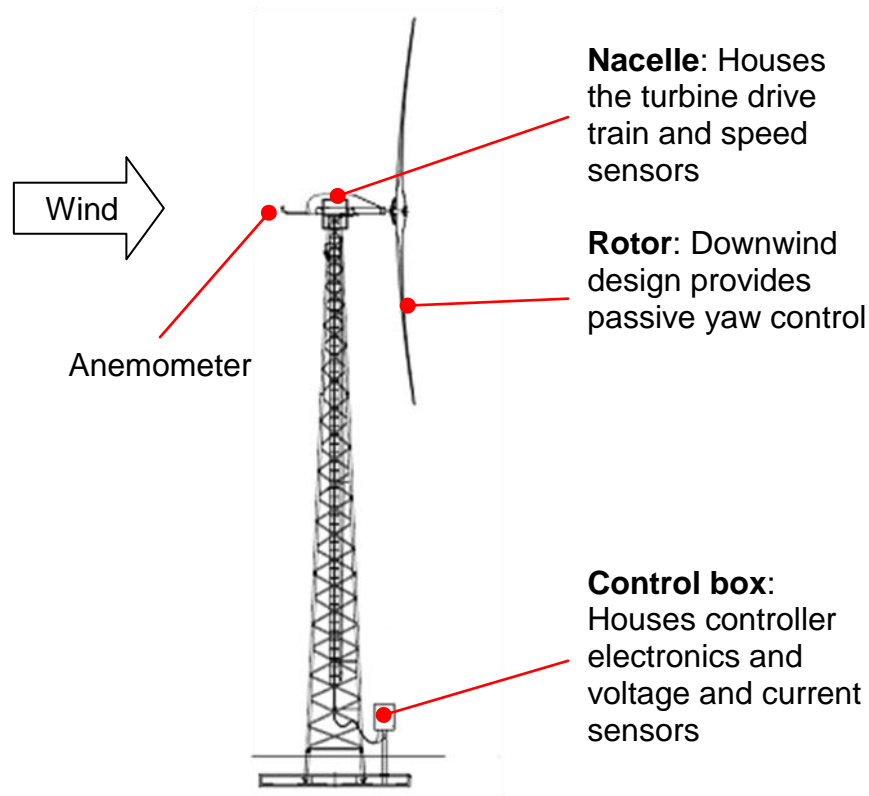


Figure 22: Gaia Wind turbine structure (Gaia Wind, 2009b)

The WTE hardware is constructed from two turbine nacelles with the rotors removed which are connected at the low speed shaft (LSS) as shown in Figure 23. The SCIM of the nacelle on the left is treated as the HUT, and is connected to a standard Gaia Wind controller. The SCIM of the second nacelle is used in motoring mode to drive the HUT. It is fed by a variable frequency inverter and the two units together constitute a variable frequency drive (VFD) as described in §2.2.6.

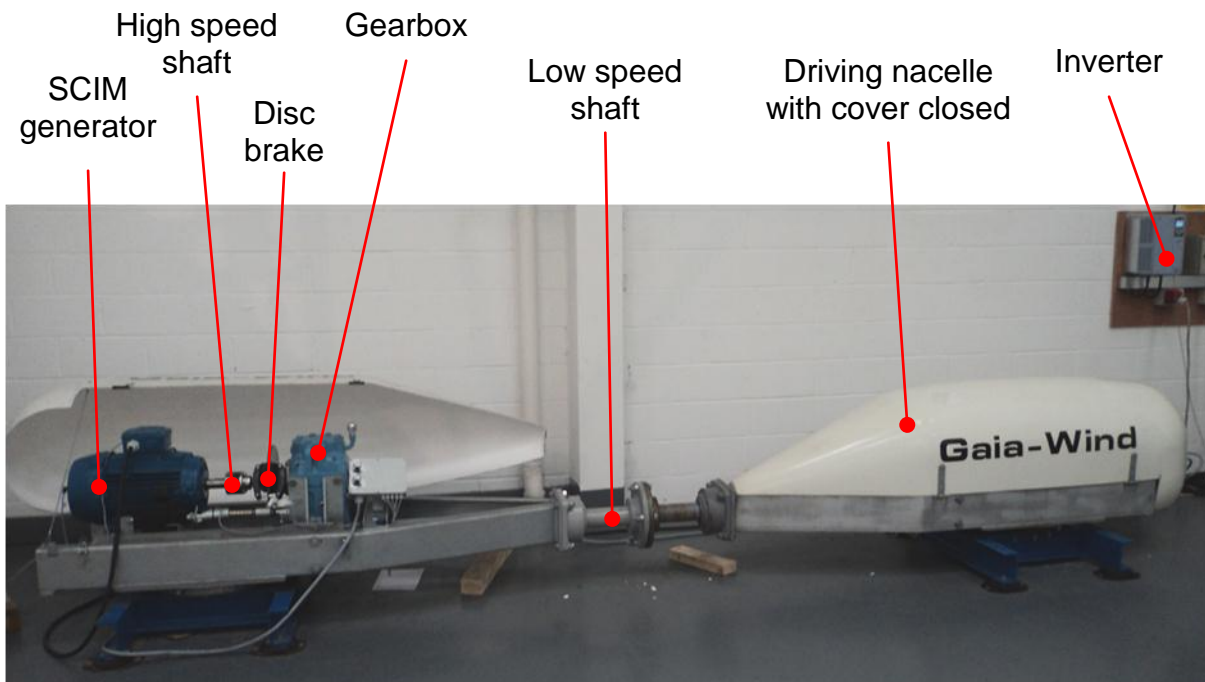


Figure 23: Gaia Wind WTE hardware layout

The general structure is a pragmatic one that takes advantage of the availability of standard equipment. However, the arrangement is not ideal since it includes energy conversion steps which are not needed and which therefore constitute unnecessary sources of power loss. In particular, the two gearboxes and low speed shaft shown in Figure 24 could be eliminated.

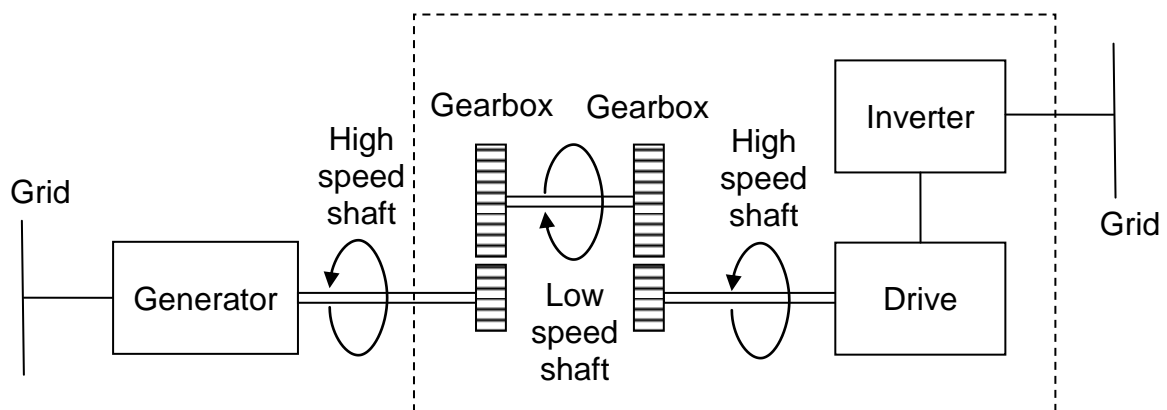


Figure 24: Schematic representation of Gaia Wind WTE

On the other hand, the structure has the advantage of being symmetrical. The gearboxes are identical and so are the drive and generator. In theory therefore, the losses should also be symmetrical, and if an overall value for system losses can be

determined, it can be divided equally between the two halves of the system. In practice, the efficiency of a SCIM operating in generating mode may not be the same as when it is operating in motoring mode, but the approximation may be reasonable in this case.

A further advantage of the Gaia hardware arrangement is that it employs the actual turbine hardware in the WTE. Previous work on WTEs (eg. Dolan et al., 2005) has typically used scaled-down hardware which introduces further potential sources of uncertainty into the results.

4.1.2 Instrumentation and control

As a fixed pitch machine, the Gaia Wind turbine relies on the aerodynamic characteristics of the rotor to induce stall at higher wind speeds to prevent over-generation. As an additional precaution however, the rotor are fitted with aerodynamic brakes which deploy if other safety systems fail. If deployed, the tip brakes need to be reset by an engineer. The downwind design provides passive yaw control which eliminates the need for a yaw drive; however, that means that tower shadow is significant.

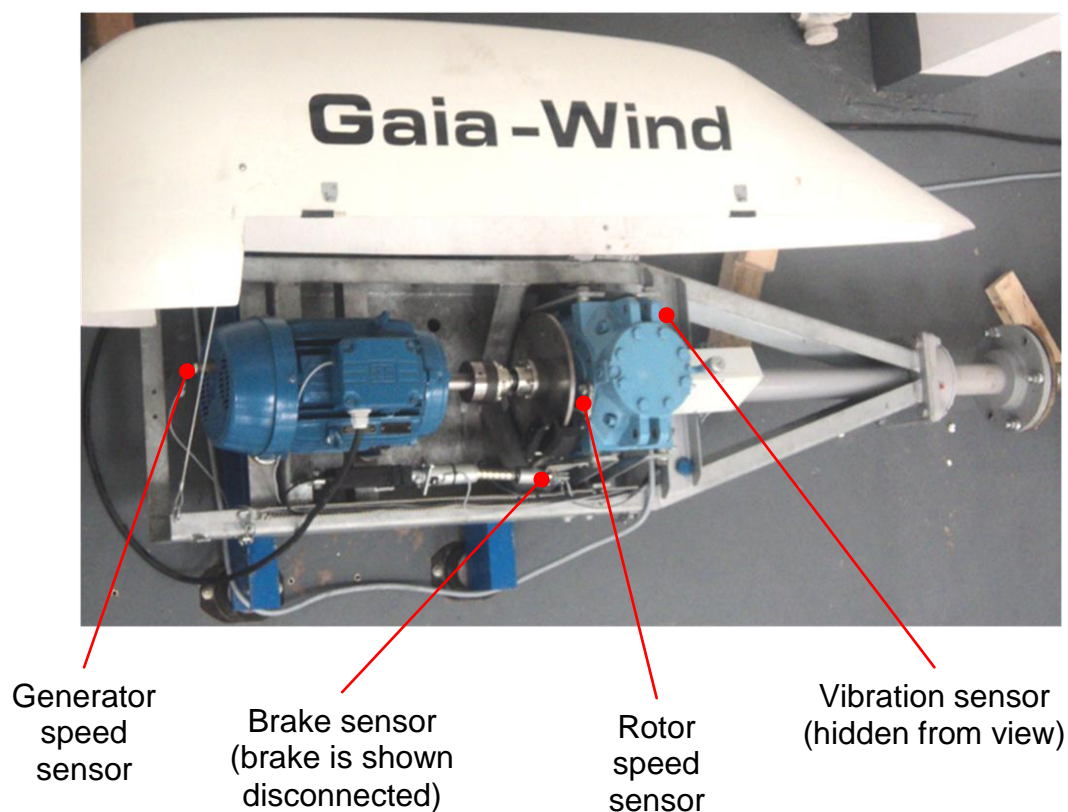


Figure 25: Gaia Wind nacelle detail

The turbine is equipped with speed sensors for both the rotor and the generator as shown in Figure 25. A brake sensor and a vibration sensor provide information about the state of the machine primarily for safety control. Not shown in Figure 25 but visible in Figure 22 is an anemometer which is positioned upwind of the nacelle to measure the instantaneous wind speed. Measurement equipment in the control box whose interior is shown in Figure 26 provides instantaneous voltage and current readings.

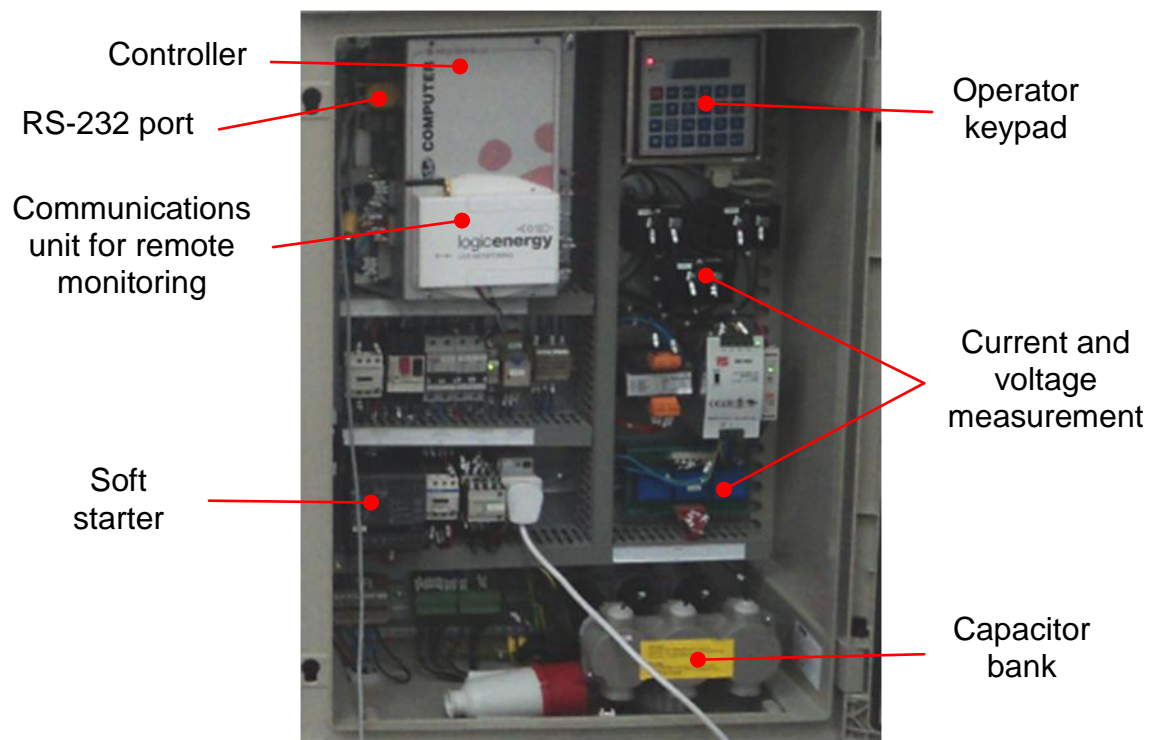


Figure 26: Gaia Wind control box detail

Under normal conditions, control of the turbine is provided by an IC1000 processor unit supplied by Danish company Mita Teknik. The controller takes input from the various sensors and generates control signals to the brake, grid connection relays and soft starter. In particular, the controller is responsible for initiating the connection to the grid when the wind speed rises above the cut-in speed of 3.5 m/s. At this time, the controller briefly activates the soft starter which puts the SCIM into motoring mode to ensure that the rotor is rotating faster than the network synchronous speed. In the WTE, the HUT is connected to a standard controller, so all usual sensor measurements are available with the exception of wind speed.

The controller unit offers an RS-232 output port for connection to a PC. The instantaneous sensor readings can be polled using the proprietary M-NET protocol whose structure is summarised in Appendix I. Two versions of the M-NET protocol are in use. The older “normal” version only provides wind speed and output power. The newer “extended” version however provides the following details:

- Wind speed (m/s)
- Rotor speed (rpm)
- Generator speed (rpm)
- Electrical output power (kW)
- Cumulative energy production (kWh)
- Status codes

4.1.3 SCIM

The squirrel cage induction machine (SCIM) that performs the function of generator in the turbine and motor in the variable frequency drive (VFD) of the WTE is a Weg Indústrias IE2 high efficiency unit whose datasheet can be found in Appendix E. The slip values quoted on the datasheet are positive showing that the unit was designed to operate in motoring mode. The question of whether its performance will be the same when operating as a generator can only be settled by experimentation which is outside the scope of this project.

For several of the machine characteristics, the datasheet provides three different values corresponding to standard voltages in different contexts. The relevant voltage in this situation is 400V, which means that where three values are shown, it is the second which is relevant.

As a six-pole machine connected to the UK distribution network at 50Hz, the synchronous speed of the generator will be 1000 rpm as explained in §2.2.6. The slightly lower speeds shown on the datasheet take the slip into account under the related load conditions.

The SCIM datasheet also provides values for power factor and efficiency at different loads. However the rated power of the SCIM is chosen to match the rated power of the wind turbine which is only achieved at the rated wind speed of 9.5 m/s. The NREL duration test report shows that rated wind speed was achieved about 26% of

the time over a 9.5 month period at the NREL test facility in Boulder, Colorado (Huskey et al., 2010). This is a fairly typical pattern which suggests that to replicate such a wind regime the SCIM of a WTE would be working with a small load. Even in this first stage project, the power input will be fairly low and drive efficiency is likely to be around 88%.

As well as important information on electrical performance, the datasheet also quotes a figure for the moment of inertia of the SCIM rotor which could be used in Eq. 11 for controlling the delivered torque in the second stage project.

4.1.4 Inverter

Together with the SCIM, the second component of the VFD is the CFW-11 IGBT inverter also manufactured by Weg Indústrias. The inverter is a wall-mounted device with the general structure shown in Figure 27. As part of this project, an additional RS-232 communications module had to be installed in the position labelled *F* in the figure.

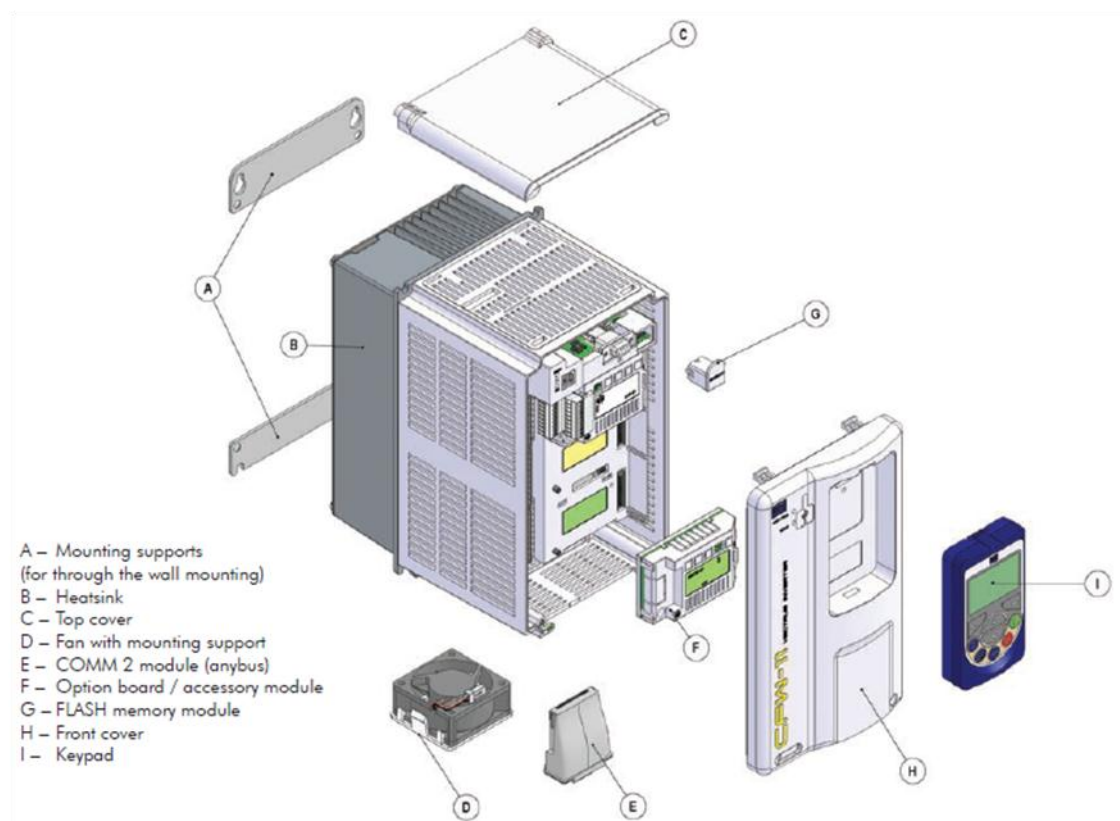


Figure 27: Weg inverter components (Weg, 2008)

The inverter, whose block diagram can be found in Appendix J, is built around a 32-bit central processing unit (CPU) which provides considerable onboard processing capability. The unit has 16 digital and two analogue sensor inputs, and offers the facility to upload control programs to the internal memory which can be written in one of the standard languages defined in the IEC 61131-3 standard including ladder logic (Weg, 2007).

The discussion in §2.3.3 highlights the need for closed loop control, and this could be provided using one of the digital input channels and the standard speed sensor on the drive SCIM; however, this was not in place in the Gaia WTE. The control of the VFD is discussed in §4.1.5 below in light of this limitation.

Constructing control programs using the Weg ladder logic authoring tool and uploading them directly to the internal CPU would appear to be an obvious and efficient approach; however, it would also have introduced difficulties in terms of the integration of data from the HUT as well as making the development of the HMI more complex. In addition, the company brief specifies Microsoft C# as the development language. C# programs running on a PC have several theoretical drawbacks, such as runtime interpretation of bytecode and communications and operating system overheads. However, the additional overhead was not deemed significant for this first stage project given a sufficiently powerful host PC and a dedicated communications link.

The operation of the inverter is controlled by setting the values of around 900 operating parameters. The programming manual (Weg, 2010) describes their use and range of values, but in summary, there are essentially three categories:

- static parameters which need to be configured in order for the inverter to perform in the particular hardware configuration, and whose values remain constant
- dynamic parameters which must be constantly monitored and adjusted by the control program to achieve the required behaviour
- read-only parameters that provide information about the state of the machine

Only some of the available parameters were relevant to this project, and much of the early familiarisation was concerned with identifying them. The complete list can be found in the software system specification in Appendix K, and Table 7 provides some

selected examples. It should be noted that the value of P0010 is the calculated output from the VFD.

Parameter	Description	Purpose
P0402	Motor rated speed	One of a set of static parameters used to characterise the motor
P0312	Serial protocol	One of a set of static parameters used to configure the serial communications channel
P0683	Serial speed ref	Dynamic parameter used to set the required drive speed
P0100	Acceleration time	Dynamic parameter used to ramp the speed over a period of time
P0010	Output power	Read-only parameter

Table 7: Example inverter parameters

4.1.5 VFD control

The CFW-11 unit offers four strategies for the control of a VFD the simplest of which is known as V/f control. In this mode, the inverter maintains a constant ratio of voltage to frequency. The developed torque is directly proportional to this ratio, and therefore a steady torque is delivered over a wide range of motor speeds (Parekh, 2004). The resulting torque-speed characteristic, shown in Figure 28, is somewhat different from that of the directly supplied induction machine in Figure 10. It is clear from the figure that V/f control is not ideal for a WTE whose purpose is specifically to control the developed torque to replicate a wind regime; however, V/f control is appropriate when the requirement is to deliver a steady motor speed as in this first stage project. Because of this requirement, the simplicity of V/f control and because V/f control is the default strategy provided by the inverter, it was adopted for this project. The Weg manual claims an accuracy of 1% of motor rated speed when the inverter is used in V/f mode.

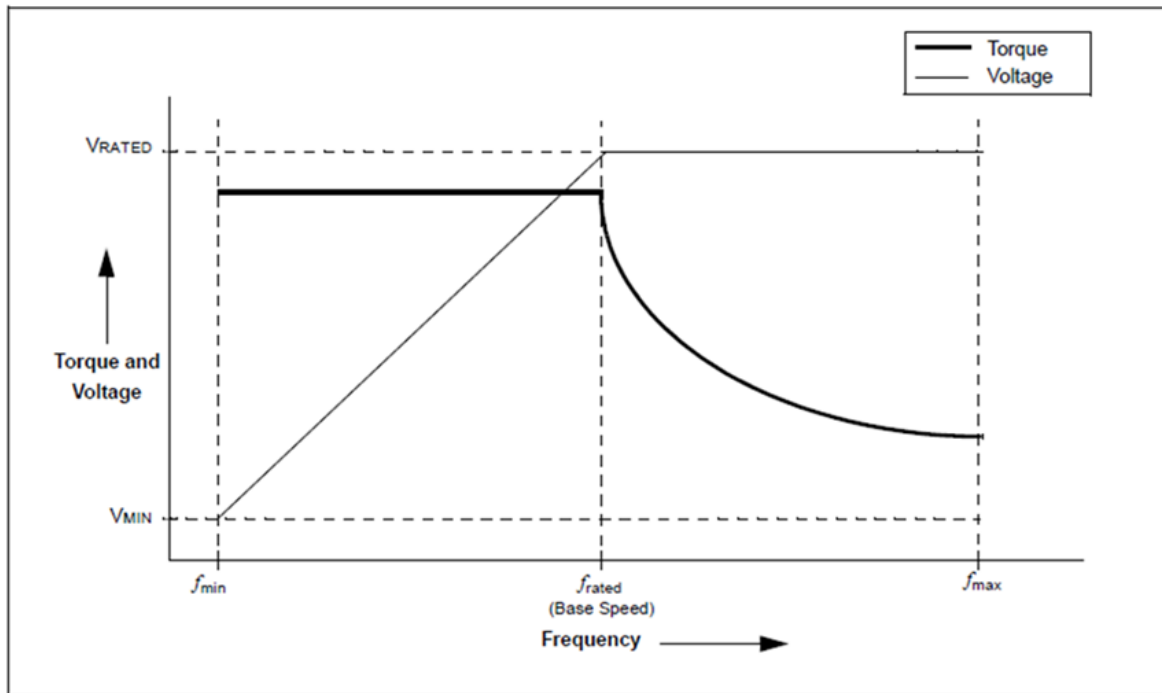


Figure 28: Torque-speed characteristic of VFD using V/f control (Parekh, 2004)

In addition to the V/f strategy, the CFW-11 provides vector control in which the motor current is divided into two components using the Park transformation as described in §2.2.7. In this mode the CFW-11 offers direct control over the developed torque.

Vector control can be used as an open loop configuration which relies solely on an accurate description of the motor via the relevant parameter values. Weg quotes an accuracy of 0.5% of rated speed in sensorless mode, whereas in a closed loop configuration using feedback from a shaft encoder, accuracy increases to 0.01%.

The fourth control strategy, Voltage Vector Weg (VVW), offers a level of performance which lies between V/f and sensorless vector control.

The second stage of the Gaia WTE development would require the use of vector control to recreate the reference torque specified by the turbine model. At that stage, the hardware configuration could also be improved by the addition of a shaft encoder to provide feedback for closed loop vector control.

4.1.6 Summary

There are some features of the Gaia hardware configuration that are likely to introduce inefficiencies into the WTE operation which will have to be compensated

for. This is a good motivation for attempting to quantify the overall efficiency of the system in the evaluation. The theoretical or quoted efficiencies of the gearbox and SCIM could provide a way of estimating the expected overall efficiency of the WTE.

4.2 Software application

The main product from this project is the software application which provides an HMI for the WTE hardware. Its design is discussed in §3.8, and this section describes the final version and discusses its limitations.

4.2.1 Overview

The design which was produced in advance of the on-site development period proved to be appropriate with no changes being requested by the company. The original plan for development needed to be changed because the WTE hardware was not accessible during the first week. The approach adopted was therefore a top-down process which began with the HMI itself with the two communications modules being developed later. While access to the hardware was restricted, communications output was viewed in a console window. This allowed communication processes to be developed step by step according to the design. As greater detail was included in the communications, the structure of the messages shown in the console window could be compared for example with the protocol definitions to ensure that they were correctly formatted. This approach proved effective with very few alterations being required once the system was connected to the hardware.

4.2.2 HMI and general system features

All of the main functions identified in the design were implemented within the three-week development period. Those minor issues that were not completed are described in §4.2.5 along with additional work that has been requested by the company in order to make the current implementation effective.

At the highest level of description, the HMI provides two modes of operation. In the automatic mode shown in the screen shot in Figure 29 the operator can define a series of steps for the system to follow (labelled 1 in the figure). Apart from the obligatory start and stop steps, each has a target speed and duration. The scripted test can be run from the toolbar or the menu.

The HMI layout for manual mode is shown in Figure 30. This illustrates how the operator may directly control the VFD by altering the speed setting directly (1). The HMI has clearly-visible start and stop controls (2) to minimise error, and the animated indicator and summary calculations are the same as in the automatic mode.

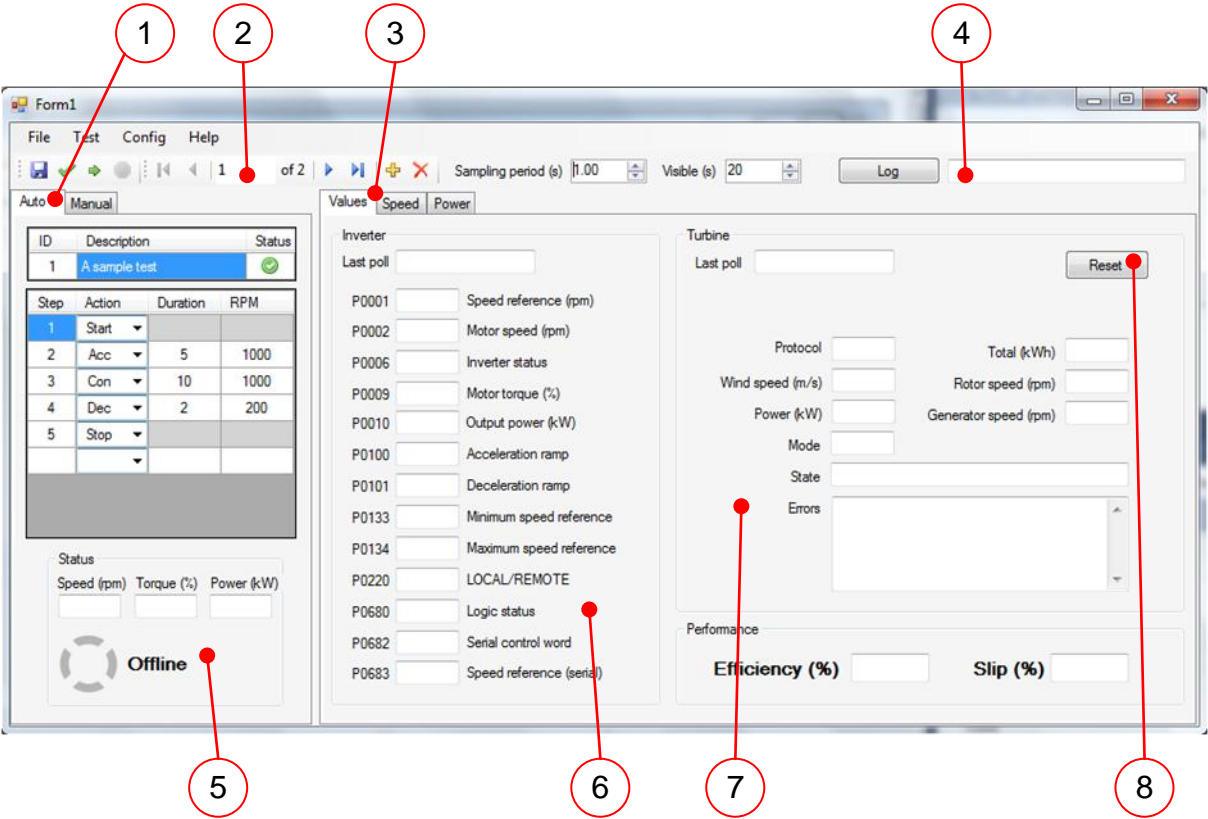


Figure 29: HMI showing Auto tab and numerical feedback

The numbered features in Figure 29 are described in Table 8.

Label	Description
1	The Auto tab allows the operator to specify a series of commands to the inverter
2	The toolbar allows the operator easy access to commands to run and stop a test, for example, and to navigate from one stored test to the next. The screenshot in Figure 29 shows that there are two tests currently stored in the internal database.
3	Output from the system is shown in one of three tabbed panels on the right. Figure 29 shows the panel which reports numerical values from the inverter and the turbine. When the WTE is active, these values are updated automatically at a polling period defined by the sampling period specified by the operator.
4	The operator can choose to log operational data to an external file in Microsoft Excel format. Again, the rate is determined by the sampling period set by the operator. The access to Excel files is achieved using the C# project ExcelPackage (Tunnicliffe, 2007) which is protected under the GNU Public Licence ⁴ .
5	The HMI has a large animated indicator to show the state of the WTE hardware to minimise the possibility of operator error. This section of the display also shows summary calculations performed by the system.
6	The values of inverter parameters are displayed on the left of the feedback panel
7	Turbine controller values are displayed on the right of the feedback panel
8	A turbine reset button which was not in the original design was included on request so that the operator can recover from error conditions such as rotor overspeed. This duplicates the function described in the user guide (Gaia Wind, 2008).

Table 8: Notes on HMI layout

Figure 30 also shows one of the alternative feedback panels which gives a graphical indication of the speed of both drive and generator (3). The third tab (not shown) offers a similar display comparing drive and generator power. Drive power is obtained from the inverter parameter P0010 which is the calculated power output of the VFD – i.e. the power input to the WTE, and generator power is the measured electrical power from the generator – i.e. overall output power. These values are the basis for the calculation of system efficiency.

The graphical displays are achieved using an open source C# project (Zimmermann, 2009).

⁴ <http://www.opensource.org/licenses/gpl-license.php>

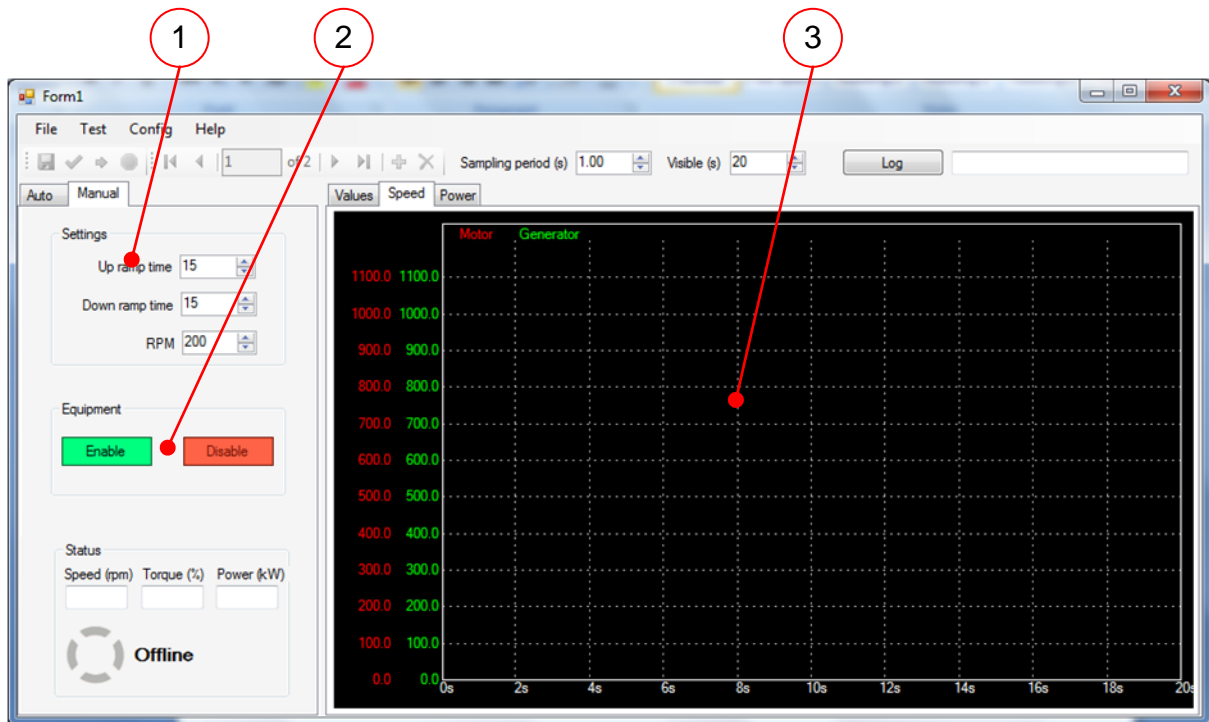


Figure 30: HMI showing Manual tab and graphical display

4.2.3 Resolved issues

The system requires a number of activities to be carried out simultaneously without interfering with each other. A multi-threaded design is therefore implemented which allows background tasks to be completed without preventing the user interacting with the interface. During the development, the need for several concurrent threads raised a number of timing issues, some of which were very time-consuming to resolve. In most cases, the solution was to use .NET events⁵.

Access to the methods of one class from within another proved difficult to implement. The eventual solution was to use the .NET delegate mechanism⁶.

In the initial design, the relationship between the different hardware elements was not clear. During the development, a *device* class was introduced. The generic features of a device could therefore be assembled in this class including the association with a serial port. Both the inverter and the turbine were represented by

⁵ <http://msdn.microsoft.com/en-us/library/awbftdfh.aspx>

⁶ <http://msdn.microsoft.com/en-us/library/ms173171.aspx>

a subclass of *device*. The final class diagram is available in the system specification in Appendix K.

4.2.4 Communications

Communications with the inverter use a subset of the industry standard Modbus protocol⁷. The required message formats are described in the Weg serial communications manual (Weg, 2010b). Messages are assembled by the application as a series of bytes which are written to the serial port. Every message generates a response which in the case of the status polling message is used to update the feedback panel in the HMI.

The turbine controller uses the proprietary M-NET protocol from Mita Teknik (see Appendix I). Messages are prepared in a similar way to those for the inverter. A main difference between the two protocols is that M-NET has specific start and end markers that encapsulate the entire message including the two bytes of cyclic redundancy check (CRC).

The communications modules were based on existing applications developed by Gaia Wind. These were largely re-worked but provided useful models. In particular, they provided ready-made solutions to the CRC calculations for both protocols.

During the development of the communications modules, two tools in particular proved useful. ModbusMat⁸ is a free application for managing and monitoring Modbus communications, and Free Serial Port Monitor⁹ displays the detail of outgoing and incoming messages over any serial port.

A major issue was discovered when trying to run the application with both inverter and turbine connected. The issue was that the RS-232 communications to both the inverter and the turbine controller were disrupted with the inverter running at low speeds. The turbine communications were also disrupted with the inverter running at higher speeds to the extent that status polling was ineffective. The problem was assumed to be the result either of electromagnetic interference (EMI) produced by

⁷ <http://www.modbus.org/specs.php>

⁸ <http://www.ataytugal.com/ModbusMat.htm>

⁹ <http://www.serial-port-monitor.com/index.html>

the inverter or the existence of ground loops when both devices were connected to the same PC. Both of these conditions are notoriously difficult to diagnose.

RS-232 is more susceptible to EMI than some other protocols because it relies on a so-called single-ended signal. Binary 1s are represented by voltage peaks on a single wire while zeros are represented by voltage troughs. Because the signal relies on a single electrical channel, voltage spikes caused by EMI are easily mistaken for signals. RS-485 on the other hand uses two wires for carrying a binary signal in which 1s are represented by a high signal on one wire and a simultaneous low signal on the second. Zeros are represented by the opposite signals on both wires. The advantage of a differential signal is that an unintended voltage spike will occur simultaneously on both wires, and will therefore be ignored.

A number of trial-and-error solutions were attempted by the Gaia Wind engineer to rule out ground loops and improve the signal quality; however, none completely resolved the issue. Table 9 summarises several alternative solutions that involved the purchase of additional equipment which were therefore also considered.

In the end, opto-isolation and RS-232 over USB were both attempted. The USB approach did not appear to make any difference despite its differential signalling. Using an opto-isolator on the inverter serial cable however did appear to solve the problem, but only when using a PC with a native serial port. When using an RS-232 to USB adapter, communications were improved but still not completely reliable. This suggests that the problem was due to a ground loop or similar effect, but also that the USB adapters might be part of the problem.

Solution	Notes
Opto-isolated RS-232	Using an opto-isolator would break the electrical circuit between the PC and the other equipment. This would guard against ground loops but probably not EMI which may be inducing spikes in the cable directly
NMEA	Specifically designed for noisy environments, the National Marine Electronics Association communication standard uses special equipment which appears very robust, but is also very expensive.
RS232 over fibre	Rules out induced or conducted interference completely; however, equipment is expensive.
RS232 current loop	Uses current pulses rather than voltage modulation to carry the signal and therefore less susceptible to spikes. Not as expensive as the previous two options, but would require some work to make up the required cables.
RS485	Very feasible in the long term for the inverter but would require a new interface module which would increase the expense. Communications with the turbine controller would require RS-232 to RS-485 adapters
RS-232 over STP	Shielded twisted pair (STP) cables are cheap and come with RJ-45 connectors, so this solution would also require the use of adapters on both channels.
RS-232 over USB	Universal Serial Bus (USB) communications are the modern PC communications standard, and like RS-485 use a differential signal. The original arrangement already made use of RS-232 to USB adapters to connect the equipment to the PC. The solution in this case would simply be to eliminate the standard serial cable by placing the adapter at the equipment end of the connection rather than the PC end.

Table 9: Possible communications solutions

4.2.5 Residual issues

Very few items were originally planned but not implemented. One of these was the facility for the operator to specify a standard directory in which to store logfiles. However, the operating system stores the location last used in the *Save File* dialog, and this is sufficient in most cases.

A further logfile item that was not implemented was the ability to open a logfile from within the application. However, since the files are in Excel format, it is a simple matter to open them using the standard operating system tools.

The help documentation for the system has not yet been implemented. This will be completed for the company after the end of the academic project.

There is one known bug in the system which related to the graphical speed and power displays. The open source project that has been used assumes that the polling period is greater than 1s. If a smaller polling period is used, the x-axis labels are incorrectly displayed. This is because the points to be labelled are identified using the modulus function, and any fractional values are effectively rounded up. Apart from the visual effect, the display and logging works correctly.

Issue logging and version control will be implemented following the end of the academic project in order to identify and resolve any further bugs.

4.2.6 Evaluation

The software was developed over a very short period of time, and as usual with short project only a minimum amount of time was available for testing. All of the major functions have been shown to operate correctly; however, a comprehensive examination of all possible error conditions has not been carried out. It is to be expected therefore that there will be unhandled exceptions from time to time when the software is in use. The company will log any such errors for fixing later.

The current class hierarchy was developed in an incremental way, and it does not therefore capture as accurate a representation of the hardware as possible. The inverter and turbine were identified as subclasses of a generic serial device; however, the same was not achieved for the two protocols used in the application. Ideally, a generic protocol class should be constructed with Modbus and M-NET as subclasses. This would also be an opportunity to accommodate the protocol

message and response variables as properties of the protocol class. Currently, these are simply program variables declared within the inverter or turbine classes.

The selection of Microsoft C# was made for practical reasons of maintainability. Although this is acceptable for this first stage project, the additional overheads incurred by running a C# application on a PC might be significant when trying to replicate a wind regime accurately. It would be useful at some future date to compare the performance of this application with an equivalent written in ladder logic and uploaded directly to the onboard programmable logic controller (PLC) of the inverter. Such a solution might still require the creation of an external HMI, however. An intermediate solution might recreate the current application in a compiled language rather than one which relies on runtime interpretation of bytecode.

A further alternative design would be to make use of the customisation features of Microsoft Excel. Because Excel already has a very robust user interface and provides for easy input, output and manipulation of data, the features of the current development could be added as part of an Excel-based application written in C#. This would retain the maintainability of the software, but would simplify the interface and eliminate the requirement for writing external Excel log files.

4.3 Test results

Although the evaluation tests had been fully specified, a number of problems have prevented their completion:

- Serial communications issues absorbed a great deal of the available time
- The need for a PC with a native serial port rather than the author's laptop meant taking that PC away from its normal use
- There were competing priorities regarding the use of the WTE hardware during the latter stages of the project
- Access to a turbine controller with the extended version of the M-NET protocol was difficult to arrange
- An error in the logging feature of the software system meant that the first tests did not provide adequate data
- The Gaia engineer was unable to help with running tests in the last few days before the deadline

At the time of writing, a number of errors in the logging function of the software have been resolved and an updated version of the software has been sent to Gaia Wind on 22nd August. However, it has not been possible to run any tests since that time, and Appendix L contains email communications between the author and the Gaia engineer regarding the logging function. To illustrate the issues with the earlier version, Table 10 shows an extract of actual data logged by the system during a test attempt run by the Gaia engineer on 18th August. The four main problems are briefly discussed below.

Timestamp	Drive RPM	Drive power (kW)	Generator RPM	Generator power (kW)	Efficiency (%)	Slip (%)
18/08/2011 11:17:08	1005	100.5	1003	65.436	65	100
18/08/2011 11:17:09	1005	100.5	1003	65.436	65	100
18/08/2011 11:17:10	1005	100.5	1005	0	0	100
18/08/2011 11:17:11	1005	100.5	1005	65.436	65	100
18/08/2011 11:17:12	1005	100.5	1005	0	0	100
18/08/2011 11:17:13	1005	100.5	1003	0	0	100
18/08/2011 11:17:13	1005	100.5	1003	0	0	100
18/08/2011 11:17:15	1005	100.5	1003	0.1	0	100
18/08/2011 11:17:15	1005	100.5	1003	0.2	0	100
18/08/2011 11:17:16	1005	100.5	1003	0.3	0	100
18/08/2011 11:17:18	1005	100.5	1003	0.3	0	100

Table 10: Logged data with errors

Incorrect drive power logged

For each row in Table 10, the value in the *Drive power* column is the value for *Drive RPM* divided by ten. The cause of this is a simple error in which the wrong inverter parameter was used. The reason for the division by ten is that all inverter values are supplied as integers even if the actual value has decimal places. The stored value therefore needs to be divided by the appropriate factor to give the actual value.

Negative generator power values incorrectly logged

Several values in the *Generator power* column in Table 10 are large positive numbers where small negative values are expected. Negative numbers are typically

represented at a low level in two's complement format¹⁰. A conversion using 4-byte two's complement has been implemented, but further test results would be required to ensure that the problem is resolved.

Error in efficiency calculation

In resolving the more obvious problems, an error in the efficiency calculation was discovered. The software inserts an Excel formula into the *Efficiency* column in the log rather than a simple numerical value. It was found that the Excel ROUND() function was applied at the wrong point leading to all decimal places being lost.

Error in the slip calculation

The slip calculation used at the point that this data was logged was that supplied in the original company brief. In fact, that calculation incorrectly used the drive angular velocity rather than the synchronous speed to calculate generator slip. This issue was raised with the Gaia engineer who agreed the correction.

¹⁰ http://en.wikipedia.org/wiki/Two's_complement

5 Forward plan

This project was intended as the first stage of a longer development. Those aspects of the fully featured WTE which were not included here naturally provide the basis for further work. In addition, the practical work of this project has revealed the potential of the hardware components and the limitations of the present approach. This section presents a series of potential projects that could follow on from the work done here.

5.1 Limitations of current implementation

As agreed with the company during the scoping of the current project, the main limitation is the absence of a turbine model. This means that the range of tests and simulations is limited to those involving a steady generator speed reference. This is adequate for benchmark testing but not for anything more realistic. In particular, it is not possible to match behaviour of the WTE with wind speeds.

The current software implementation uses the V/f control mode of the inverter. This does not allow direct control over the generated torque which would be a necessary step on the way to a fully featured WTE.

The current hardware does not support closed loop control of the VFD. Although the inverter manual suggests that sensorless vector control provides speed control precision of 0.5% or rated speed, it does not make any claims about the precision of torque control. Adding a shaft encoder to the drive would theoretically increase speed control precision to 0.01% of rated speed, and is recommended for dynamic performance and torque control (Weg, 2010).

The behaviour of the SCIM used as both motor and generator in the American version of the turbine does not seem to correspond to that expected on the basis of its datasheet (Appendix F) judging by the examination of the NREL data (Appendix G). Independent testing of the unit in the WTE would help to determine its operating characteristics with greater reliability. Direct measurement of the resistance and reactance of the stator windings using standard tests would verify the value provided on the datasheet, and also allow the direct calculation of generated torque.

The absence of appropriate comparator data makes the verification of the measurements from the WTE impossible at this stage. Logged data from a European

version of the turbine would be sufficient, but data from controlled tests would provide a more reliable benchmark.

5.2 Alternative implementations

One category of possible future project explores the possibilities offered by using different platforms and development tools. C# was used as a development tool on request; however, §4.2.6 outlines other ways in which the same functionality might have been delivered. Alternative implementations would allow direct comparisons between different toolsets with respect to efficiency of operation and ease of use and maintenance. Some possibilities are discussed below.

5.2.1 *Excel*

Rebuilding the current project as an extension to Microsoft Excel using either C# or Visual Basic would require less new work to develop the user interface and would also perhaps be easier to use due to the users' familiarity with Excel. With less code devoted to the user interface, maintenance may also be easier.

5.2.2 *Weg Ladder Programming*

Although a lower level programming environment, WLP may offer greater efficiencies due to its independence from an operating system. In a second stage project aimed at providing closed loop torque control, it is likely that ready-made components would be available for implementing proportional, integral and derivative control.

5.2.3 *Real-time operating systems*

Some previous studies such as Munteanu et al. (2010) have mentioned the use of real-time operating systems for the efficient processing of signals to and from the WTE hardware. Although no further details are provided, this is probably a reference to a Unix variant that is optimised for real-time processing. An equivalent development could be produced using Ubuntu¹¹ for example, with the interface code built in Java. The likelihood of this approach delivering a more efficient overall system is not as strong given that Munteanu was using a DC drive which requires simpler control. The use of a SCIM and VFD may well deliver equivalent

¹¹ <https://wiki.ubuntu.com/RealTime>

performance and control; however, the Java/Ubuntu alternative would provide the opportunity to verify this.

5.2.4 MATLAB

The majority of previous WTE studies make use of the MATLAB¹² development environment. Specifically designed for scientific computing application, MATLAB provides many features for developing algorithms, for performing numerical computations efficiently and for visualising data. MATLAB would provide similar benefits to using Excel in that less effort would be required to develop the HMI. In addition, MATLAB is specially designed to accommodate sensor input.

5.2.5 Increased instrumentation

The use of a shaft encoder on the VFD has already been mentioned in the context of closed-loop control. Other sensors could be added to the WTE hardware to provide verification of the inverter and turbine controller feedback. A torque transducer on the turbine-side high speed shaft for example would provide a direct measurement of the developed torque. Crabtree (2011) and Hus Wen-Ko (2010) describe the use of different type of sensor for the detection of various kinds of fault condition. The scope of the WTE could easily be expanded in this way to support different kinds of test.

5.3 Inclusion of turbine model

The turbine model has been researched as part of this project, and its implementation is the obvious next stage of the WTE development. However, there are several identifiable steps towards this goal.

5.3.1 Vector control

Taking advantage of the facilities provided by the Weg inverter, the type of control could be changed from V/f to sensorless vector without altering the overall functionality of the current software. This would require a similar range of activities to the current project, and would provide the basis for moving forward.

¹² <http://www.mathworks.com/products/matlab/>

5.3.2 Steady torque control

Replicating the torque produced by a turbine rotor entails direct control over the torque developed by the VFD. Allowing the user to provide target torque values via the HMI is not particularly intuitive, however. Instead, this step would require a minimal turbine model which would provide a reference torque value based on a wind speed value. In the first instance, the WTE would allow steady state operation with respect to a particular wind speed input, and transition between states in the same way that the current application does for speed inputs.

5.3.3 Variable torque control

This advanced version of the system would implement a full turbine model including torque oscillation. It would also allow the user to provide input in the form of a variable wind speed reference, either from a wind signal generator like those described by Diop et al. (2007), or from logged data. The implementation would require the use of standard control techniques such as proportion-integral (PI) control as used by Fleming et al. (2009) or proportional-integral-derivative (PID) control as used by Monfared et al. (2007).

5.3.4 Advanced control investigation

Once the WTE is capable of replicating a variable wind profile, the development focus could change to examine the control algorithms themselves. A question for a project at this level would be whether the standard control algorithms are sufficiently dynamic to replicate the profile accurately. One of the characteristics of a realistic wind profile is that there is a significant stochastic element. Control algorithms designed to track a steady reference are not necessarily best suited to such a signal, and work would focus on more experimental control approaches.

5.4 Laboratory-based simulation

A further category of further projects involves the construction of tools to aid the development process itself. At present, access to the hardware configuration at the Gaia Wind premises is essential for any further development. This bottleneck could be eased by the development of simulations of the major hardware components.

5.4.1 Weg inverter simulation

The current application defines a limited interface with the CFW-11 inverter through the manipulation of a subset of its available parameters. The behaviour of the unit could however be simulated using some of the same methods as in the current project. This would make it possible to develop the WTE software further in the laboratory with field testing on the Gaia hardware at a later stage. An inverter simulation could take the form of a C# application on a separate PC replicating the appropriate subset of inverter behaviour over a serial communications link.

5.4.2 Other simulations

Gaia Wind is currently investigating the use of a GenDrive¹³ back-to-back inverter to decouple the turbine generator from the distribution network in a departure from the Danish model. A future simulated version of the inverter would allow parallel development of the turbine control system. This raises the possibility of developing a library of equipment simulations along the lines described in §5.4.1 each of which could be the subject of a short project.

¹³ <http://www.gendrive.co.uk/>

6 Conclusions

6.1 Comparison with aims and objectives

The overall aim of this project was achieved in full, with the inclusion of all the major functions in the software system that was developed. It was also possible to introduce a few unplanned features such as the possibility of resetting the turbine controller via the HMI.

It quickly became clear during initial discussions with the company that there would not be sufficient time or resources available to complete the development of a fully-featured WTE in one stage. The scope of the project was therefore set at a lower level, and this decision has been shown to be appropriate. The current system addresses the immediate needs of the company for a simple interface for performing benchmark testing on new turbines before shipping. However, it does not include the more involved modelling of turbine behaviour seen in the previous studies reviewed in §2.3. Neither does it fully exploit the control capabilities of the CFW-11 inverter, and in hindsight it would probably have been possible to use sensorless vector control rather than the much simpler V/f approach from the outset. This only became clear during the project, however, and to change the approach mid-way would have introduced a much greater degree of complexity. This would have put the overall completion of the project within the agreed timescale at risk.

6.1.1 *Review of current relevant literature*

A substantial range of previous WTE studies was identified during the literature review, and a consistent picture of WTE requirements duly emerged. An early focus on WTE studies also identified the relevant aspects of turbine design which set the content requirements of the rest of Chapter 2. From several points of view, therefore, the literature review has been successfully delivered.

There are two main ways in which the literature review could be improved from its current version. Firstly, a more consistent treatment of the central theme of the replacement of turbine rotor torque by a simulated prime mover would improve the focus. Currently, these issues are discussed, but not tied together as well as they could be.

The second improvement that could be made would be to draw the relevant equations together into a single consistent formula for WTE control. Eq. 3 and Eq. 11 form the basis of such a model, but the final combination was not presented. This could be done relatively easily, but would require more time that is available to the academic project. On the other hand, since the current development does not include a turbine model, such a synthesis can legitimately be left to the follow-up development.

6.1.2 Hardware investigation

The capabilities of the hardware components of the Gaia Wind WTE were successfully characterised, as demonstrated by the operation of the software. This investigation was necessarily pragmatic in that it focussed on the requirements of this particular project, rather than aiming to extract an optimum configuration. Such an approach might for example have led to the use of sensoreless vector control rather than V/f control, but would have taken longer. In terms of the current project aim, this objective is successfully delivered, and has also revealed useful directions in which the WTE can be developed in the future.

6.1.3 Software development

The delivered software performs according to the initial requirements, and can therefore be considered successful. A major problem late on in the development was the disruption of the RS-232 communication signals that prevented a full evaluation of the results. This was partly the result of a lack of access to the WTE hardware in the first week of development which led to a review of the schedule. Had the original schedule been adhered to, the inverter communications module would have been tackled in the first week. This would probably have led to the discovery of the communications issues earlier, and this might have made a solution possible in time to carry out the evaluations fully. This is speculation, however, since efforts to resolve the communications problems might have reduced the time spent on other features.

6.1.4 Evaluation of the project outcomes

As alluded to in the previous section, the evaluation of the project outcomes is the weakest part of the project since time and other resources were very short towards

the end of the project period. Apart from the incorrect recording of values in the log file, the software has been shown to work correctly according to the specification and a procedure for reporting and resolving future problems has been established with the company.

A good deal of subjective evaluation of the work of the project has been presented at various stages of the report. The objective of evaluation of results can therefore be considered partially successful.

6.1.5 Definition of programme of future work

§0 sets out three types of project that could follow from this one, with several examples under each heading. Clearly the most important of these is to continue the development to the planned second stage with the inclusion of a turbine model. Even this, however, can be broken down into smaller steps providing the basis for a number of development projects.

The other two categories of project involve the development of comparable systems using other platforms and tools, and the development of facilities to support the future developments themselves.

6.2 Personal reflection

To attempt an MSc dissertation project of this type over a single semester was an ambitious undertaking, even given the reduced scope of this initial project. There were many unknowns at the outset which included not only the details of the turbine subsystems, but also the .NET development environment. The knowledge gaps were largely filled simply by putting in long hours, but this approach has been reasonably successful.

Setting the scope of the project to its current definition was a deciding factor in the success of the project, and the author was guided strongly in this by the Gaia Wind engineer. The immediate requirements of the company were relatively straightforward and at the basic level constituted a fairly standard software development project. Some of the material covered in the literature review is not directly relevant to this, and from that point of view less effort could have been expended in that area. However, a deep investigation into previous WTE work has

eventually delivered a much richer background to the current project. This is valuable not only to the author personally, but also to potential follow-up projects.

There was an element of risk involved with the chosen project selection process which was dependent on receiving replies for the companies that were approached. A back-up plan was prepared, however, which meant that the risk was adequately managed. Ideally, the project should have started earlier than it actually did, but the negotiation with possible partner organisations took longer than expected. This was another factor that contributed to the intensity required during the development period. With this one drawback, the approach was very successful, and has led to the establishment of contacts with a series of companies that may lead to other student projects in the future.

The weakest part of the project is the evaluation which had to be curtailed for a number of reasons. The author struggled for some time to formulate a reasonable evaluation method for the project. Part of the reason for this was the simple nature of the software: because the turbine model had been excluded, there appeared to be insufficient grounds for comparing performance of the WTE with any other installation.

The design of the software makes use of object-oriented principles, but this was not previously the author's primary area of expertise. A number of technical lessons were learned along the way, and the final result is less than perfect. Some generalisations such as the relationship between the two communications protocols were not identified until late on in the development and were therefore not captured. There was also a reliance on simple software applications previously developed at Gaia Wind which were not based on object-orientation. This has led to some inconsistencies in the construction of the software that might cause some initial confusion for future developers working with the current code. The current version performs adequately, however, and the experience has provided insights into many aspects of object-oriented development and the use of the .NET framework.

Appendix A: Email to potential partners

Dear XXXXXX

I hope you don't mind me contacting you out of the blue, but you are listed as the main contact for XXXXXXXX on the Scottish Renewables Web site.

I am a member of the teaching staff in the School of Computing at Edinburgh Napier University, but also over the last two years I have been doing a Masters degree in Energy and Environmental Engineering. My intention is to complete the MSc dissertation over the summer, and I am looking for an external partner organisation with a practical requirement that could form the basis of a project. My main interest is in the control and instrumentation of renewable energy devices, but I would also be interested to discuss other possibilities. I have attached my CV for reference, and I would be grateful if you could forward this message to the appropriate person in the company.

Thanks very much

Brian Davison

Programme Leader,
BSc Information Technology
Edinburgh Napier University
0131 455 2373

Appendix B: Initial company brief

(extracted from an email from the Gaia Wind engineer)

Project has been reduced to just providing a Piece of Software to Control the Test bed.

You would plan to be here from 27th June for three continuous weeks. With regards to the project, I'd like you to use C# Express to develop the application for a these reasons, it'll make it easier for me to work with the project later, I already have some Modbus and some Gaia Comms code written which hopefully will give you a head start. It will also mean I should be able to help more plus I have books etc which might be useful.

I'd like to break the project down into a few separate outcomes, which we should aim to complete consecutively, so that if the time line slips we at least have the early stuff complete.

Stage1: Inverter Control Module

Modbus Code Module to Start Motor, Stop Motor, Set Acceleration, Set Deceleration, set Speed. It should be able to read Motor Power and RPM. Plus a basic Test Application.

Stage2: Gaia Query Module

Module to Get the Power Data from the controller. Our current version of control firmware has Wind, Power, Energy and errors available. The firmware in development also has Generator and Rotor RPMs. I already a small application in C#, though it might need a little tidying up.

Stage 3: Overall Application

User Interface to Display Live... Drive Motor Speed and Power, Generator Speed (If available) and power. There should be two 'modes' Manual mode and Auto Mode

In Manual Mode you can set Speed, Acceleration, Deceleration and Start/Stop the Inverter.

In Auto Mode, there should be a start button that runs a script. Script should be text based so it can be edited easily (XML perhaps?) but each entry should be something like this.

[bool Run][Acc Value][Decc Value][Speed][Time]

Example1

Start, Accelerate over 10 seconds, Decelerate don't care, Speed = 1000, 60 seconds. The time wouldn't start counting down until actual speed = set speed.

[1][10][10][1000][60]

Example2

Bring the Motor to a stop over 10 seconds, Time = 0

[0][10][10][0][0]

Example3 – Test Run

[1][10][10][1000][60] // Enable Drive Accelerate up to 1000 rpm over 10s then spend 60 seconds at speed

[1][2][10][1010][60] // Enable Drive Accelerate up to 1010 rpm over 2s then spend 60 seconds at speed

[1][5][10][1050][60] // Enable Drive Accelerate up to 1050 rpm over 5s then spend 60 seconds at speed

[0][10][10][0][0] // Stop the drive and disable decelerate to zero over 10 seconds

You should also be able to set a sample period from 1-300s. This can be part of the script or part of the UI. Every time this period elapses a data entry should be made in an XL or Tab delimited file:

Time	Drive RPM	Drive kW	Gen Rpm	Gen kW	Efficiency %	Slip %
8/5/2011 8:45	1020	6.5	1010	5.5	$(5.5/6.5)*100$	$(1010/1020)*100$

Appendix C: Project proposals

Gaia Wind proposal version 1

Student Name	Brian Davison	Matriculation Number	02014147
Title	Simulation of wind regime and wind turbine response in a physical test rig		
Summary of work to be undertaken during project	<p>The Gaia Wind 11kW is a two-blade, fixed pitch, fixed speed turbine for small applications. Gaia Wind Ltd. is currently developing a test rig which consists of two turbines without rotors connected so that one can be used as a motor to drive the other. The turbine acting as a motor is fed by a Weg CFW-11 inverter which has the facility for programmatic control. The ultimate goal is to be able to provide a file of logged wind data, and for the inverter to accurately recreate the wind forces via the motor so that the behaviour of the passive turbine can be observed. The main challenges are therefore</p> <ul style="list-style-type: none"> a) To produce an accurate model of real turbine behaviour which reflects the response lag due to inertia in the rotor b) To construct a control program for the Weg inverter which implements the model and also compensates for losses in the test rig itself c) To evaluate the results of the control algorithm against the original logged wind and turbine data <p>The first part of the project will be to produce a review of current literature on turbine testing and wind regime modelling.</p> <p>The practical phase of the project will include the following activities</p> <ul style="list-style-type: none"> a) Collection of wind and turbine data from at least one site b) Familiarisation with the Weg inverter and the selection of appropriate control methods. c) Analysis of the wind and turbine data to identify the nature of the turbine response to changes in wind speed and direction d) Implementation of the derived model in software for control of the inverter e) Iterative refinement of the program to compensate for physical losses and inertia in the test rig <p>The evaluation phase will involve the correlation of the original logged turbine data with that observed in the test rig to determine the effectiveness of the model and the software implementation.</p>		
Deliverables	<p>Consider the academic challenges that you will face and what solutions you proposed to deliver as part of the project and consider what will make the project a success. There should be no more than 5.</p> <p>[N.B. Approved deliverables will be compared with your final report.]</p> <ul style="list-style-type: none"> 1. Literature review 2. Mathematical model of turbine behaviour 3. Inverter control software 4. Evaluation of results 		

Resources required	<ul style="list-style-type: none"> a) Physical test rig at Gaia Wind Ltd. facility in Glasgow b) Wind and turbine data – to be collected from a live site. Some data may also already be available c) Appropriate software for Weg inverter programming – available from Weg
Proposed Supervisor	Tom Grassie

Gaia Wind project version 2

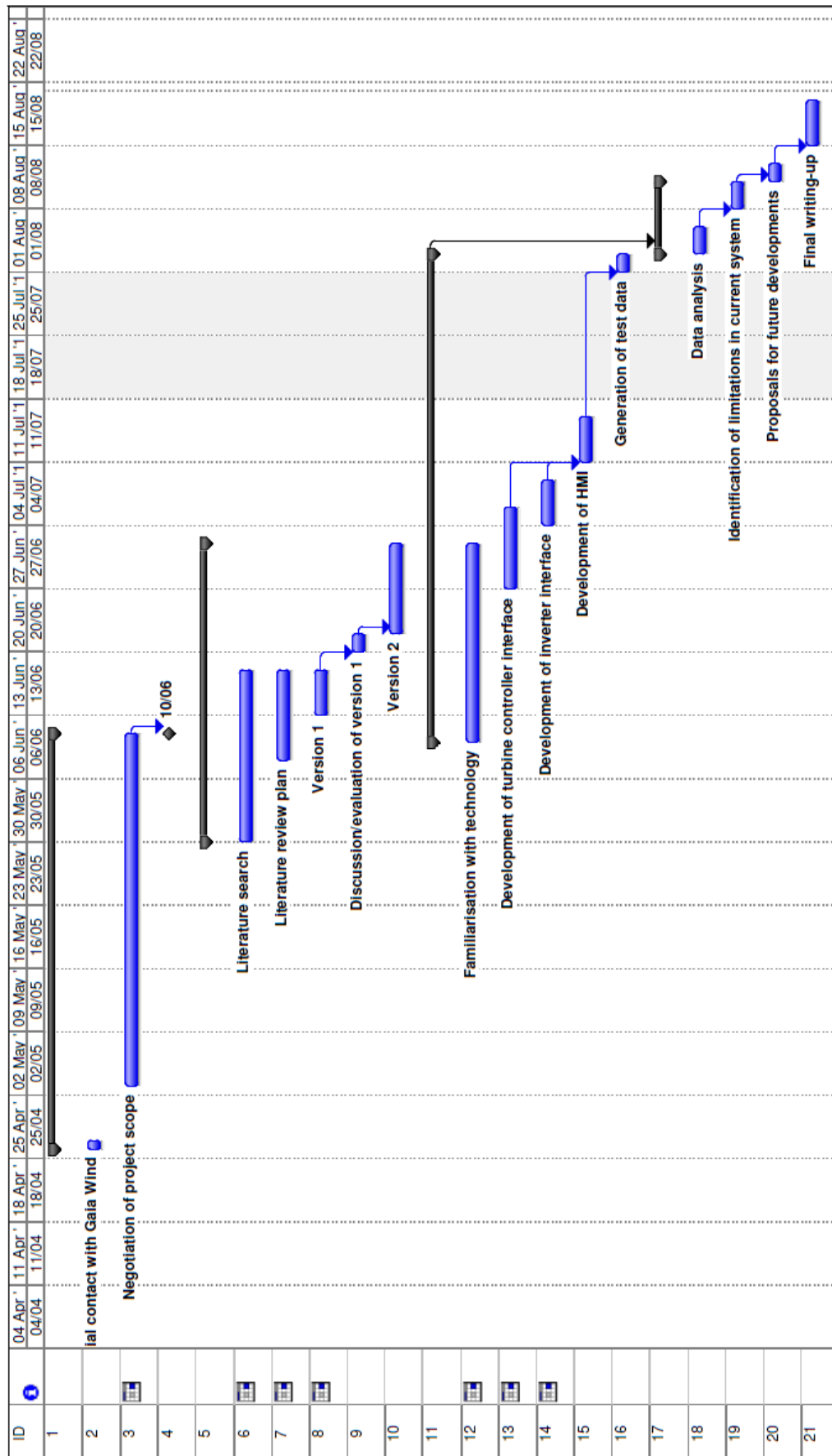
Student Name	Brian Davison	Matriculation Number	02014147
Title	Development of basic control system for a wind turbine emulator		
Summary of work to be undertaken during project	<p>The Gaia Wind 11kW is a two-blade, fixed pitch, fixed speed turbine for small applications. Gaia Wind Ltd. is currently developing a test rig which consists of two turbines nacelles connected hub to hub so that one can be used as a motor to drive the other. The motor element is fed by a Weg CFW-11 inverter which has the facility for programmatic control. The ultimate goal is to be able to read a file of logged wind data, and for the inverter to accurately recreate the equivalent forces via the motor so that the behaviour of the passive turbine can be observed. This project will be concerned with the initial stage of the development, which is to develop a basic control system for the inverter. This will allow the user to specify a sequence of steady state inputs to be fed to the motor and the duration of each state so that response of the turbine under test can be observed. Data from the onboard turbine controller will be used to provide process feedback. Based on this initial development, a plan for further improvements to the control algorithms can be constructed.</p> <p>The main challenges are therefore</p> <ul style="list-style-type: none"> a) To identify the capabilities of the available hardware components b) To design and develop appropriate communications interfaces between the hardware components and a master PC application c) To identify and measure appropriate variables for analysis and control d) To ensure that the basic system takes into account the longer-term goals of the development <p>The first part of the project will be to produce a review of current literature on turbine testing and test rig instrumentation and control.</p> <p>The practical phase of the project will include the following activities</p> <ul style="list-style-type: none"> a) Familiarisation with the hardware components and the selection of appropriate technologies for communications and control. b) Development of appropriate communications and human-machine interfaces c) Evaluation of the basic control system and the identification of promising options for further development. 		

Deliverables	<ol style="list-style-type: none"> 1. Literature review 2. Specification of initial control system 3. Communication and control software and documentation 4. Evaluation of results 5. Forward plan for development
Resources required	<ol style="list-style-type: none"> a) Physical test rig at Gaia Wind Ltd. facility in Glasgow b) Documentation for hardware components – available from manufacturers c) Interface hardware to be supplied by Gaia Wind
Proposed Supervisor	Tom Grassie


Contingency proposal

Student Name	Brian Davison	Matriculation Number	02014147
Title	Reactive control of a micro wind turbine		
Summary of work to be undertaken during project	<p>Micro wind turbines are typically located in urban environments where local turbulence interferes considerably with their efficient operation. Turbulence effects occur over a small time scale, and to compensate for them a control approach would need to react to rapidly changing conditions. This contrasts with more stable environments in which control strategies are geared to achieving and maintaining a steady state in relation to a given set point.</p> <p>This project would investigate the range of available data that could be used to drive a reactive control strategy, and would use a programmable logic controller (PLC) to provide yaw control via a brake on the turbine mount. Evaluation would be carried out by comparing the output from the turbine with and without active control under similar wind conditions.</p>		
Deliverables	<p>Consider the academic challenges that you will face and what solutions you proposed to deliver as part of the project and consider what will make the project a success. There should be no more than 5.</p> <p>[N.B. Approved deliverables will be compared with your final report.]</p> <ol style="list-style-type: none"> 1. Literature review 2. Model of the relationship between selected parameters and brake activation 3. Hardware solution including sensor, PLC and brake 4. PLC control program 5. Final evaluation of results 		
Resources required	<ol style="list-style-type: none"> a) Access to micro wind turbine at Edinburgh Napier b) Hardware components (sensor, wiring, PLC, brake, etc) c) PLC programming software 		
Proposed Supervisor	Tom Grassie		


Appendix D: Project plan



Appendix E: Weg 50Hz SCIM datasheet

		WEG Indústrias S.A.		Nr.: 043360/2010-A													
				Date: 26-APR-2010													
DATA SHEET Three-phase Induction Motor - Squirrel Cage																	
Customer : Product code : Product line : IE2 - HIGH EFFICIENCY																	
Frame : 160L Output : 11 kW Frequency : 50 Hz Poles : 6 Rated speed : 970-970-975 rpm Slip : 3.00-3.00-2.50 % Rated voltage : 380-400-415/660-690V Rated current : 22.9-22.3-22.3/13.2-12.9 A L. R. Amperes : 160-156-156/92.3-90.5 A I/In : 7.0 No load current : 11.7-13.0-14.2/6.74-7.54 A Rated torque : 108-108-108 Nm Locked rotor torque : 210-240-260 % Breakdown torque : 240-270-290 % Design : N Insulation class : F Temperature rise : 80 K Locked rotor time : 13-13-13 s (hot) Service factor : 1.00 Duty cycle : S1 Ambient temperature : -20°C to +40°C Altitude : 1000 m.a.s.l			Enclosure : IP55 (TEFC) Mounting : B3T Rotation : Both Aprox. weight* : 133 kg Moment of inertia : 0.1760 kgm² Sound Pressure Level : 56.0 dB(A) (global)														
			<table border="1"> <thead> <tr> <th>Load</th> <th>Power factor</th> <th>Efficiency (%)**</th> </tr> </thead> <tbody> <tr> <td>100%</td> <td>0.81-0.79-0.76</td> <td>89.6-89.6-89.6</td> </tr> <tr> <td>75%</td> <td>0.76-0.72-0.68</td> <td>89.6-89.6-89.6</td> </tr> <tr> <td>50%</td> <td>0.62-0.58-0.54</td> <td>89.0-88.5-88.0</td> </tr> </tbody> </table>			Load	Power factor	Efficiency (%)**	100%	0.81-0.79-0.76	89.6-89.6-89.6	75%	0.76-0.72-0.68	89.6-89.6-89.6	50%	0.62-0.58-0.54	89.0-88.5-88.0
Load	Power factor	Efficiency (%)**															
100%	0.81-0.79-0.76	89.6-89.6-89.6															
75%	0.76-0.72-0.68	89.6-89.6-89.6															
50%	0.62-0.58-0.54	89.0-88.5-88.0															
			<table border="1"> <thead> <tr> <th></th> <th>Bearing</th> <th>Quantity (lubricant)</th> </tr> </thead> <tbody> <tr> <td>Front</td> <td>6309-C3</td> <td>13 g</td> </tr> <tr> <td>Rear</td> <td>6209-Z-C3</td> <td>9 g</td> </tr> </tbody> </table> <p>Lubrication interval: 20000 h Grease - Polyrex EM - ESSO</p>				Bearing	Quantity (lubricant)	Front	6309-C3	13 g	Rear	6209-Z-C3	9 g			
	Bearing	Quantity (lubricant)															
Front	6309-C3	13 g															
Rear	6209-Z-C3	9 g															
Notes: Temperature detector type Klixon.																	
The figures given herewith are regarded as guaranteed values and applied to sinusoidal power supplied motors, within permissible tolerances under IEC 60034-1. Noise level with tolerance of +3 dB(A). (*) Weight value can be changed without previous notification. (**) Efficiencies according to the indirect method of IEC 60034-2-1:2007 with stray load losses determined from measurement.																	
Performed alood	Checked AUTOMATICO	Revision Nr.: 0	Date: 26-APR-2010	Approved													

Appendix F: Weg 60Hz SCIM datasheet

	WEG Indústrias S.A.		Nr.: 051172/2010-B																						
			Date: 14-MAY-2010																						
DATA SHEET Three-phase Induction Motor - Squirrel Cage																									
Customer : WEG ELECTRIC MOTORS UK LTD Product code : Product line : IE2 - HIGH EFFICIENCY																									
Frame : 160L Output : 12,5 kW Frequency : 60 Hz Poles : 6 Rated speed : 1170-1170 rpm Slip : 2,50-2,50 % Rated voltage : 440-480V Rated current : 22,4-21,9 A L. R. Amperes : 157-153 A II/In : 7,0 No load current : 11,0-13,0 A Rated torque : 102-102 Nm Locked rotor torque : 210-250 % Breakdown torque : 240-280 % Design : N Insulation class : F Temperature rise : 80 K Locked rotor time : 13-13 s (hot) Service factor : 1,00 Duty cycle : S1 Ambient temperature : -20°C to +40°C Altitude : 1000 m.a.s.l		Enclosure : IP55 (TEFC) Mounting : B3T Rotation : Both Aprox. weight* : 133 kg Moment of inertia : 0,1760 kgm² Sound Pressure Level : 59,0 dB(A) (global)																							
		<table border="1"> <thead> <tr> <th>Load</th> <th>Power factor</th> <th>Efficiency (%)**</th> </tr> </thead> <tbody> <tr> <td>100%</td> <td>0,81-0,75</td> <td>89,6-90,4</td> </tr> <tr> <td>75%</td> <td>0,76-0,68</td> <td>89,6-90,1</td> </tr> <tr> <td>50%</td> <td>0,63-0,55</td> <td>89,0-88,5</td> </tr> </tbody> </table>	Load	Power factor	Efficiency (%)**	100%	0,81-0,75	89,6-90,4	75%	0,76-0,68	89,6-90,1	50%	0,63-0,55	89,0-88,5	<table border="1"> <thead> <tr> <th></th> <th>Bearing</th> <th>Quantity (lubricant)</th> </tr> </thead> <tbody> <tr> <td>Front</td> <td>6309-C3</td> <td>13 g</td> </tr> <tr> <td>Rear</td> <td>6209-Z-C3</td> <td>9 g</td> </tr> </tbody> </table>			Bearing	Quantity (lubricant)	Front	6309-C3	13 g	Rear	6209-Z-C3	9 g
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Front	6309-C3	13 g																							
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Notes:																									
The figures given herewith are regarded as guaranteed values and applied to sinusoidal power supplied motors, within permissible tolerances under IEC 60034-1. Noise level with tolerance of +3 dB(A). (*) Weight value can be changed without previous notification. (**) Efficiencies according to the indirect method of IEC 60034-2-1:2007 with stray load losses determined from measurement.																									
Performed swilson	Checked AUTOMATICO	Revision Nr.: 0	Date: 14-MAY-2010	Approved																					

Appendix G: NREL data

Wind speed	Power/kW	Cp	Ω /rpm	Ω /rad/s	Ω_{HSS} /rad/s	Ω_{HSS} /rpm	λ	C_Q	Q
0.49	-0.08	-8.43							
1.03	-0.08	-0.93							
1.52	-0.08	-0.29							
2.01	-0.08	-0.12							
2.5	-0.08	-0.07							
3	-0.10	-0.04							
3.49	-0.11	-0.03	55.55	5.82	125.65	1199.88	10.83	0.00	0.88
3.99	0.31	0.06	55.57	5.82	125.70	1200.38	9.48	0.01	-2.47
4.49	1.15	0.16	55.60	5.82	125.76	1200.89	8.43	0.02	-9.14
4.99	2.28	0.23	55.62	5.82	125.81	1201.39	7.59	0.03	-18.12
5.49	3.67	0.27	55.64	5.83	125.86	1201.90	6.90	0.04	-29.16
5.99	5.00	0.29	55.67	5.83	125.92	1202.40	6.33	0.05	-39.71
6.49	6.27	0.28	55.69	5.83	125.97	1202.90	5.84	0.05	-49.77
7	7.57	0.27	55.71	5.83	126.02	1203.41	5.42	0.05	-60.07
7.49	8.70	0.25	55.74	5.84	126.07	1203.91	5.07	0.05	-69.01
7.99	9.80	0.24	55.76	5.84	126.13	1204.42	4.75	0.05	-77.70
8.49	10.77	0.22	55.78	5.84	126.18	1204.92	4.47	0.05	-85.35
9	11.67	0.20	55.81	5.84	126.23	1205.42	4.22	0.05	-92.45
9.5	12.36	0.18	55.83	5.85	126.28	1205.93	4.00	0.04	-97.87
10	13.12	0.16	55.89	5.85	126.41	1207.13	3.80	0.04	-103.79
10.49	13.69	0.15	55.94	5.86	126.54	1208.33	3.63	0.04	-108.19
11	14.15	0.13	56.00	5.86	126.66	1209.54	3.47	0.04	-111.71
11.49	14.59	0.12	56.05	5.87	126.79	1210.74	3.32	0.04	-115.07
12	14.80	0.11	56.11	5.88	126.91	1211.95	3.18	0.03	-116.61
12.49	14.90	0.09	56.16	5.88	127.04	1213.15	3.06	0.03	-117.29
13	15.00	0.08	56.22	5.89	127.17	1214.35	2.94	0.03	-117.96
13.49	14.93	0.07	56.28	5.89	127.29	1215.56	2.84	0.02	-117.29
13.99	14.80	0.07	56.33	5.90	127.42	1216.76	2.74	0.03	-116.15
14.48	14.60	0.06	56.39	5.90	127.54	1217.96	2.65	0.02	-114.47
15	14.40	0.05	56.44	5.91	127.67	1219.17	2.56	0.02	-112.79
15.48	14.49	0.05	56.50	5.92	127.80	1220.37	2.48	0.02	-113.38
16.03	14.42	0.04	56.55	5.92	127.92	1221.57	2.40	0.02	-112.72
16.5	14.15	0.04	56.61	5.93	128.05	1222.78	2.34	0.02	-110.50
16.99	14.24	0.04	56.67	5.93	128.17	1223.98	2.27	0.02	-111.10
17.5	14.13	0.03	56.72	5.94	128.30	1225.18	2.21	0.01	-110.13
17.99	14.08	0.03	56.78	5.95	128.43	1226.39	2.15	0.01	-109.63
18.48	13.91	0.03	56.83	5.95	128.55	1227.59	2.09	0.01	-108.20
18.99	14.00	0.03	56.89	5.96	128.68	1228.79	2.04	0.01	-108.80
19.45	14.11	0.02	56.94	5.96	128.80	1230.00	1.99	0.01	-109.55
19.92	13.74	0.02	57.00	5.97	128.93	1231.20	1.95	0.01	-106.57

Appendix H: NREL analysis

In 2009 and 2010, NREL carried out a series of tests on the Gaia Wind turbine according to the International Electrotechnical Commission (IEC) standards. The reports are now published and constitute a reliable description of the operation of a real turbine. The most relevant report is the result of the power performance test (Huskey et al., 2009) which includes binned wind speed data with corresponding instantaneous power and power coefficient as shown in Appendix G. Combining this information with the published turbine details (Gaia Wind, 2009) a number of other measures can be derived including angular velocity of the high speed shaft and load torque. However, there are two main limitations with this approach:

- Because the current project does not include a turbine model, the overall performance of the two cases cannot be directly compared
- The American grid operates at 60 Hz, and therefore a different gear ratio and model of generator are used

Ideally, the torque-speed characteristics of the two generators could be compared to identify any major differences in behaviour. Because the grid frequencies are different however, the synchronous speed will be different in each case, and two completely different models of generator have to be used. The significant divergence between the two cases means that a direct comparison will have little validity. A closer examination of the NREL data does however reveal some interesting aspects.

The NREL dataset provides power output and a power coefficient value for a range of wind speeds from 0.49 m/s to 19.92 m/s at intervals of roughly 0.5 m/s. The starting point for a meaningful comparison would be to generate a dataset from the WTE for this same wind speed range. Because the WTE does not yet include a turbine model, this cannot be done directly, and the corresponding high-speed shaft angular velocity must first be derived for each data point in the NREL data. Thus the comparison would be limited to the performance of the generators.

A speed for the high speed shaft can be derived from the rotor speed. Three NREL reports provide a range for the rotational speed for the turbine rotor; unfortunately they are not consistent. The power performance report (Huskey et al., 2009) quotes 56-62 rpm, the generator duration test report (Huskey et al., 2010) quotes 0-62 rpm, and the generator function and safety test report (Huskey et al., 2010b) quotes 60-62

rpm. The reasons for this discrepancy are not explained, which is puzzling given the continuity of the testing team for the three reports. However, it is possible to argue away some of the differences. The duration test aims to assess among other things material degradation over time and the dynamic behaviour of the turbine (Huskey et al., 2010, p. 1). It may therefore be important to consider the starting and stopping of the turbine as a potential source of fatigue, and hence the inclusion of low rotor speeds in the range 0-56 rpm. The power performance test, on the other hand, is concerned with the turbine's power output, and therefore only rotor speeds above and immediately below the generating threshold are of interest. At rotor speeds of less than 56 rpm it is assumed that the controller has isolated the turbine from the distribution network. The safety and function test is more concerned with extreme conditions and explicitly refers to the dynamic behaviour of the turbine at rated and higher wind speeds. Hence the higher range of speeds quoted (60-62 rpm). The reports are consistent on other specification parameters. The Gaia Wind turbine datasheet (Gaia Wind, 2009) quotes 56 rpm as the nominal rotor speed which corresponds to the speed required to produce 11kW at rated wind speed. This can be verified by applying Eq. 2 using the design tip speed ratio of 4, the rated wind speed of 9.5 m/s and the rotor radius of 6.5 m:

$$\lambda = \frac{\Omega R}{U}$$

$$\Omega = \frac{\lambda U}{R}$$

$$\Omega = \frac{4 \times 9.5}{6.5}$$

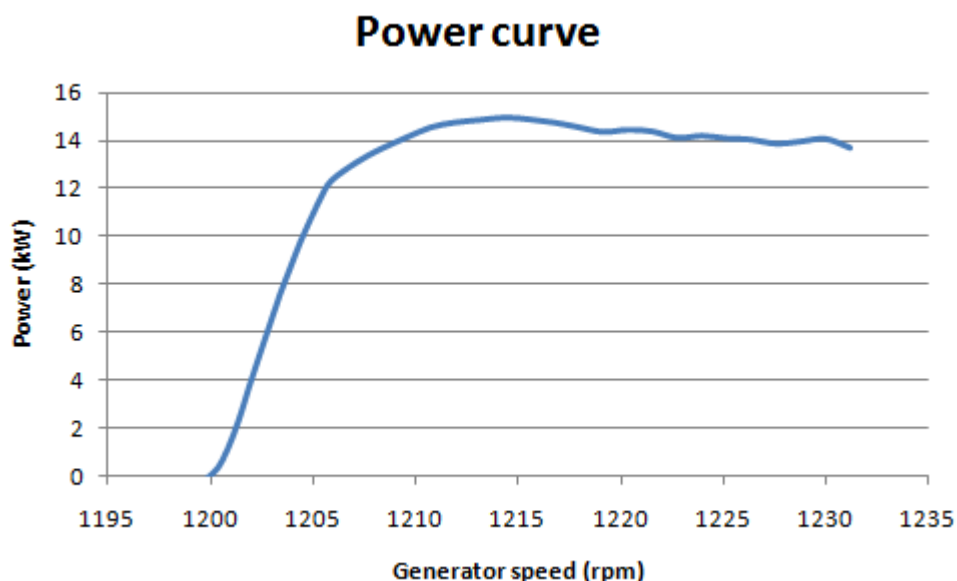
$$\Omega = 5.846 \text{ rad/s}$$

Converting to rpm:

$$\Omega = \frac{5.846 \times 60}{2\pi}$$

$$\Omega = 55.83 \text{ rpm}$$

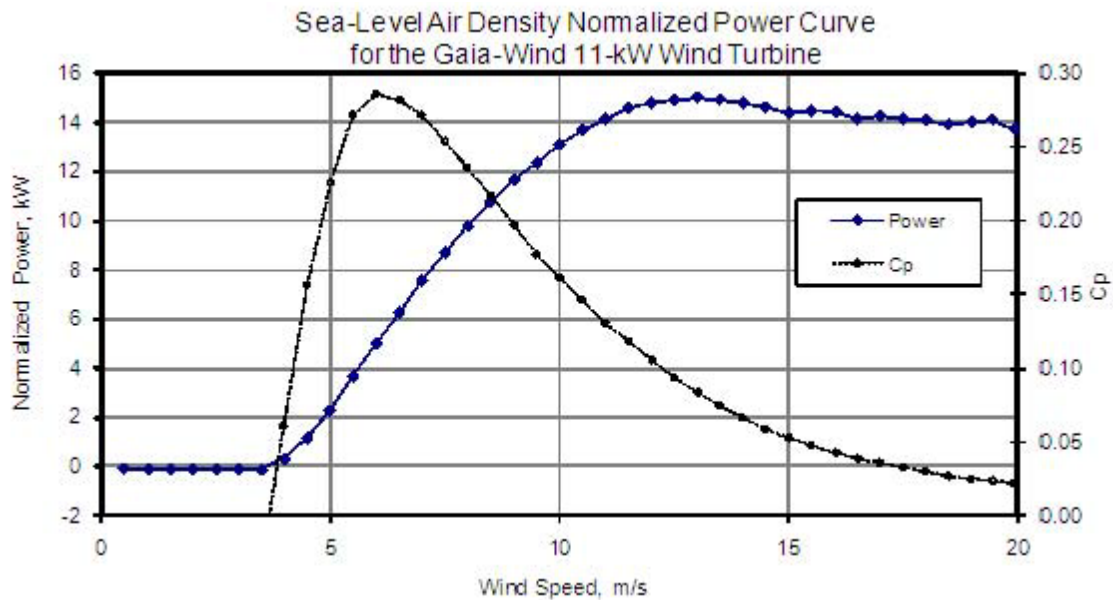
The synchronous generator speed of 1200 rpm (on a 60 Hz grid) corresponds to a rotor angular velocity of 55.55 given the gear ratio of 1:21.6. The rotor must reach this speed in order to generate power rather than draw it from the grid. From the NREL data, this occurs at a wind speed between cut-in at 3.5 m/s and 4 m/s. Thus the rotor angular velocity is assumed to increase steadily from 55.55 rpm to 55.83 rpm between cut-in speed and rated speed. Thereafter up to cut-out speed, the angular velocity is assumed to increase steadily to 57 rpm at a wind speed of 20 m/s. This is lower than the maximum rotor speeds suggested by the NREL reports; however, it was noted that the highest wind speed in the NREL dataset was 20 m/s whereas the cut-out speed is quoted as 25 m/s. This estimated high bound for rotor speed was checked with the Gaia Wind engineer. The interpolation was performed using Microsoft Excel. The result, which is tabulated in Appendix G, yields the graph in the figure below when the power coefficient is plotted against high speed shaft (HSS) angular velocity.



An interesting feature of this graph is that power output remains considerably higher than the rated value at HSS speeds greater than approximately 1205 rpm.

Comparing this graph to the power curve in the NREL power performance test report (shown in the next figure) it can be observed that the form is similar, and that similar high outputs were measured at wind speeds between 9.5 and 20 m/s. The level of power output can be explained with reference to the test procedure in which the

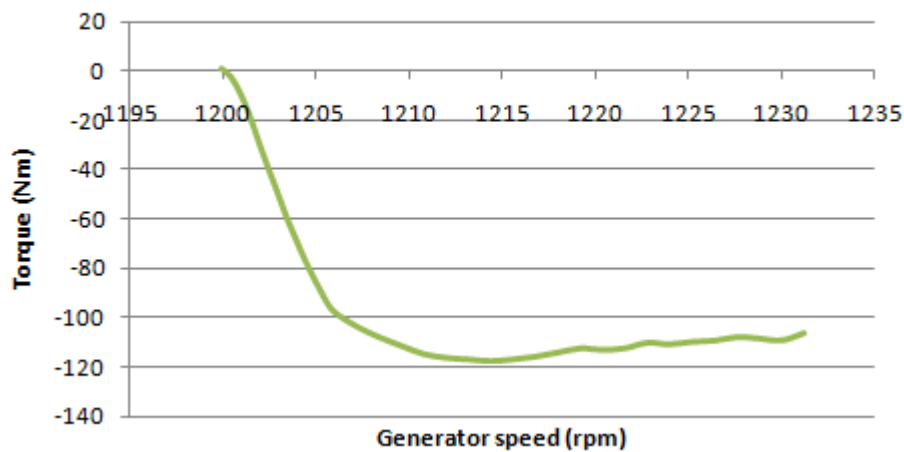
measured data is normalised to sea level. The test results represent the adjusted figures and because air is slightly denser at sea level (1.225kg/m^3) than at the test location (95kg/m^3), the power output appears raised. The effect of a higher value for air density can be seen in Eq. 1. The high broad curve is characteristic of a two-bladed turbine, and can be compared with the curves in Figure 2.



(Huskey et al., 2009)

Torque is calculated by applying Eq.8 to the values for output power and the synchronous speed of 1200 rpm. The result, shown below, has the correct form, but raises some questions about the performance of the generator compared to the reference values provided on the manufacturer's datasheet.

Partial torque-speed characteristic



Theoretically, the main inflection in the torque-speed characteristic should occur at the so-called breakdown torque. According to the datasheet for the 60 Hz generator, which is provided in Appendix F, breakdown torque is 280% of rated torque. Since rated torque is given as 102 Nm, breakdown torque should be 285.6 Nm; however, in the calculated torque-speed graph above, the main inflection occurs at around -120 Nm, barely 117.6% of the rated value. The sign is negative because the SCIM is in generating mode and so only the absolute value is needed for comparison. The reason for this substantial discrepancy is not clear, and suggests the need to test the behaviour of the SCIM in isolation.

Appendix I: M-NET protocol

(Extract from the Mita Teknik IC1000 manual)

1. The format of the request packet 60133

The request packet must have the following format:

SOH	Destination (2-255)	Source	Packet type	Data count	Data	CRC	EOT
1	x	1	EAE5	1	Xx	xxxx	4

The CRC is the CRC-CCITT applied to 'Destination', 'Source', 'Packet type', 'Data count' and 'Data ' Below is shown an example requests to node 2, where data:

1- Stop

01 02 01 EA E5 01 01 A5 81 04

2 –Reset

01 02 01 EA E5 01 02 95 E2 04

4 –Start

01 02 01 EA E5 01 04 95 24 04

5. The format of the reply packet 60132

The reply packet will have the following format:

SOH	Dest.	Source	Packet type	Data count	Data	CRC	EOT
1	1	x	EAE4	x	Rotor RPM Gen. RPM Event no. Mode local/remote wind speed Act. power Total Prod. No. of SC SC1 SC2	x	4

The size of the packet will depend on the number of active status codes. In the above table, 'Source' is the node number of the answering controller. 'Data count' will depend on active status codes, and will be 12 + 'No. of SC'. The 'CRC' calculation is the same and applied to the same fields as in the request packet – except that the 'Data' field should also be included here. Below is an example of a communication from a PC sending as node number 1 to an IC1000 controller with node number 2:

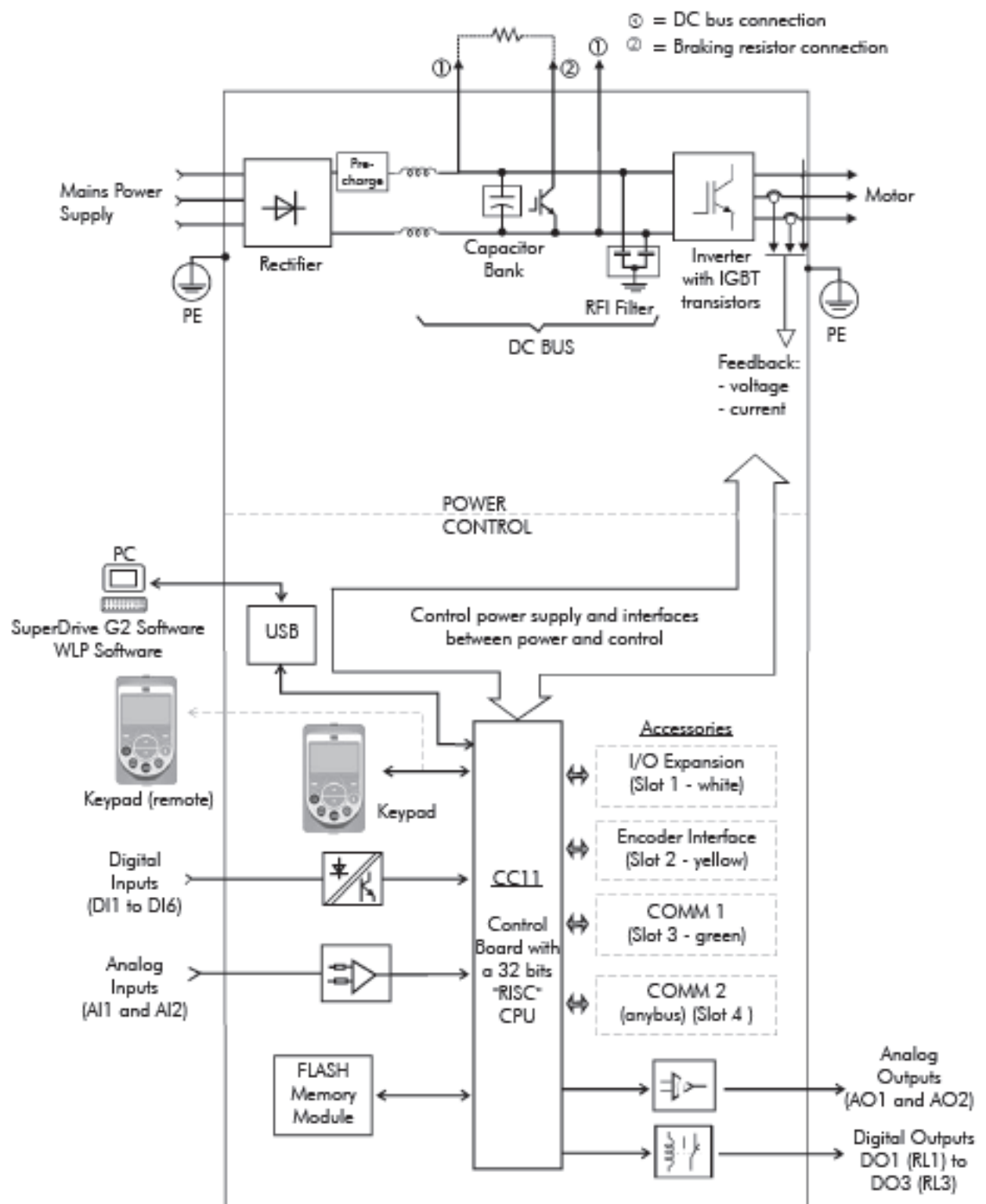
[TX] - 01 02 01 EA E5 00 01 0F D0 04

[RX] - 01 00 02 EAE4 14 0024 0294 0019 0001 003A
 |Start|To| From| type|count|Rotor RPM|Gen RPM| event |mode |wind speed|
 36RPM 660RPM F/W G1 Rem. 8 (5.8m/s)

00002012 00000016 00 00 12A5 04
 act. Power| Acc. Power|no. of SC| SC's| CRC | stop|
 8210W 22kWh

Rotor RPM 0024h = 36 RPM
 Generator RPM 0294h = 660RPM
 Event 19h = event 25 : Freewheeling ..G1
 Mode 1 = Remote mode
 Wind speed: 003Ah = 58d = 5.8m/s
 Power prod: 00002012h = 8210W
 Total prod: 00000016h = 22kWh
 Numb. of SC*2: 0000h = 0 active status codes

Appendix J: Weg CFW-11 block diagram



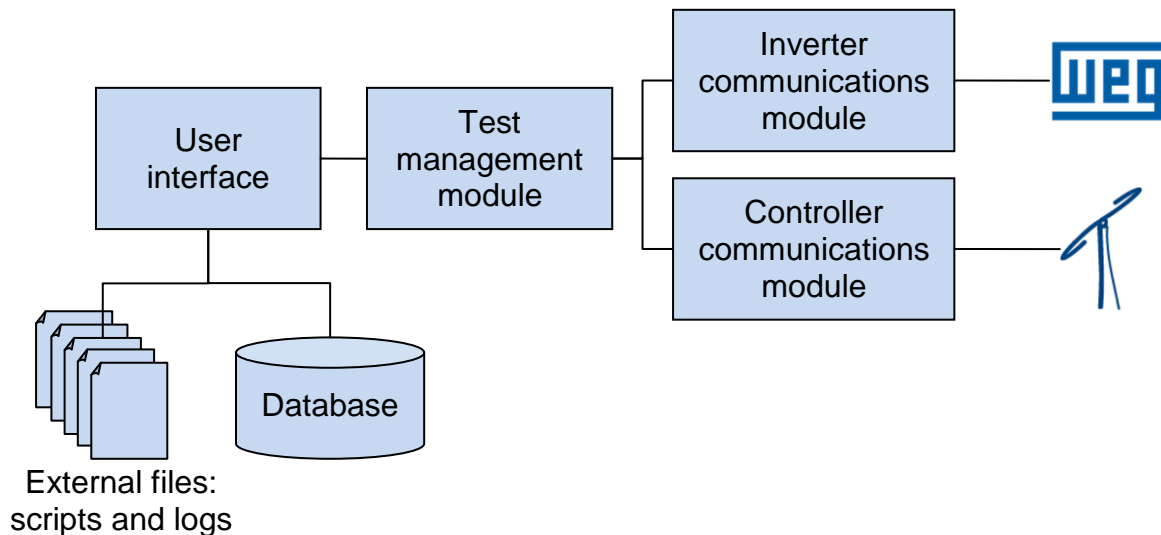
Appendix K: System specification

1 Introduction

The information in this document constitutes a starting point for the design of a control system for the Gaia Wind turbine emulator. The development approach will be based on agile development principles, and therefore further design details will emerge as the project progresses.

1.1 Overview

The system design is based on the central concept of a *Test* object which is made up of a sequence of *Instructions*. The main components of the system are shown in the block diagram below.



The system will be implemented in C# which means that the main system components will be represented by a set of C# classes. The user interface will be built from standard interface controls provided by Visual Studio, and the remaining classes will be designed independently based on the UML analyses below.

Communications with the hardware components have not been fully specified at this time because there are several options which remain to be investigated. It is likely that these will rely on code already developed by Gaia Wind.

1.2 Manual and automatic operation

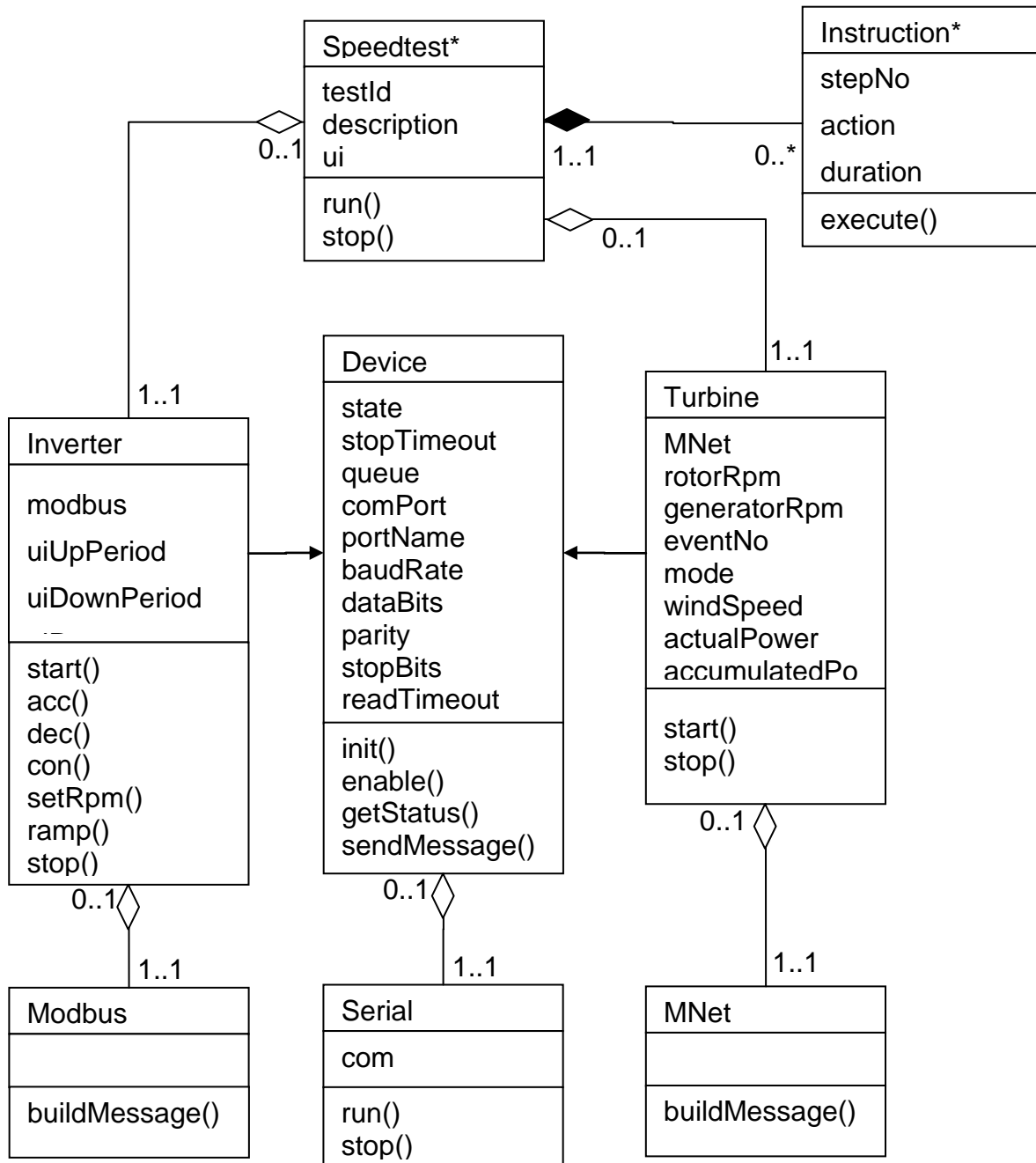
The design provides a tabbed layout with one tab for manual operation and another for automatic. The manual tab allows the user to control the inverter directly by setting an acceleration and deceleration ramp time and a speed. Two buttons enable and disable the converter. If a non-zero speed is set before the inverter is enabled, the acceleration ramp time is used. Likewise, if the speed is non-zero when the disable button is clicked, the deceleration ramp time is used. If the drive is already running and the speed value is changed, the instruction is sent directly to the inverter. Although the ramp settings are still active, their effect in this case will be negligible.

On the automatic tab, the user is able to enter a sequence of instructions directly into the interface and run. Instruction lists can be as long or as short as the user requires which allows the user to build up a sequence of instructions to suit immediate purposes. The current set of instructions can then optionally be saved to the internal database for later re-use, or exported to an external file in XML format.

The use of an internal database is intended to simplify the user interface development, and to provide better management for the tests themselves and for any logfiles that are generated. Specifically, there may be many logfiles generated for a single test which is run on different occasions, and the database maintains the link between logfiles and test. The user interface can therefore list all logfiles for a particular test on request, and the user can view or delete them.

2 Class diagram

Classes marked with an asterisk have corresponding database tables.



3 Interface design

The general layout corresponds to that of a standard Windows application with drop-down menus and a toolbar in automatic mode. In the sketches below, only four icons are shown on the toolbar, but in fact there would be one for each menu option.

Menu items are described in the following table, and the subsequent section provides some additional detail on the layout.

3.1 Menu items

Menu	Item	Description	Notes
File	New	Clears screen for new input.	Not available while test is running
	Open	Dialog allows user to select an existing test from the database.	Not available while test is running
	Save	Saves current test to the database	Not available while test is running. Instructions are validated before saving, and if errors are found, the save operation fails.
	Import	Allows the user to read test details from an external XML file	Not available while test is running
	Export	Allows the user to save the current test as an external XML file	Not available while test is running
	Delete	Deletes current test from the database and clears screen	If test has not previously been stored, <i>Delete</i> has the same effect as <i>Open</i>
	Exit	Closes the application	Not available while test is running. User is prompted to save current test if changes have been made
Test	Validate	Check current sequence of instructions against validation rules	Only available if changes have been made
	Run	Runs the current test	Not available while test is running. If changes have been made, the instructions are validated before running. If errors are found, the run operation fails.
	Stop	Interrupts the current run	Only available while test is running. Brings the drive to a graceful stop and disables.
Log	Directory	Allows the user to select a directory for storing logfiles	Not available while test is running

- B. The sequence of instructions that make up a test are shown in a vertically scrolling table. The details can be entered or altered manually, or they can be loaded from an external XML file using the option on the *File* menu.
- C. Only a restricted set of actions are possible, and they can be chosen by the user from a drop-down list. The available actions and their meanings are shown in the table below. Note that *Acc* and *Dec* could have been replaced by a single action meaning *Change to the following speed*; however, using *Acc* and *Dec* indicate the intention of the user, and can therefore be used for validation.

Action	Description	Duration (s)	RPM
Start	Start the inverter	Greyed out	Greyed out
Acc	Accelerate	Duration of acceleration	Target value
Dec	Decelerate	Duration of deceleration	Target value
Con	Remain at constant speed	Duration of steady state	Speed to be maintained
Stop	Stop the inverter	Greyed out	Greyed out

- D. The speed and power displays are intended to show instantaneous values and a continuous trace against time. Two sets of values are shown in each panel, one for the drive and the other for the generator.
- E. This box is used to set the sampling period for the speed and power traces. It also determines the period of the logfile entries.

4.2 Validation

There are a number of obvious validation rules that can be applied to a sequence of instructions. Clicking the *Validate* button causes the system to apply the rules to the sequence of steps currently displayed, and to report any errors. The table below lists the validation rules that correspond to specific actions. In addition to these, all tests must finish with a *Stop* instruction.

Action	Validation rule	Meaning
Start	Inverter state = off	Inverter state is <i>off</i> by default.
Start	$n = 1$	Can only occur as first instruction
Acc	Inverter state = on	Test must start with a <i>Start</i> instruction
Acc	$0 \leq \text{Duration} \leq \text{Duration}_{\max}$	Duration cannot be negative
Acc	$\text{RPM}_{n+1} > \text{RPM}_n$	Target speed must be greater than current speed
Acc	$\text{RPM}_{n+1} < \text{RPM}_{\max}$	Target speed must not exceed limit
Dec	Inverter state = on	Test must start with a <i>Start</i> instruction
Dec	$0 \leq \text{Duration} \leq \text{Duration}_{\max}$	Duration cannot be negative
Dec	$\text{RPM}_{n+1} < \text{RPM}_n$	Target speed must be less than current speed
Dec	$\text{RPM}_{n+1} \geq 0$	Target speed may not be negative
Con	Inverter state = on	Test must start with a <i>Start</i> instruction
Con	$\text{RPM}_{n+1} = \text{RPM}_n$	Target speed must be equal to current speed
Con	$0 \leq \text{Duration} \leq \text{Duration}_{\max}$	Duration cannot be negative
Stop	Inverter state = on	Test must start with a <i>Start</i> instruction
Stop	$\text{RPM}_n = 0$	Previous instruction must bring the drive to standstill
Stop	$n = n_{\max}$	Can only occur as last instruction

4.3 Changing speed

In cases where the acceleration and deceleration ramps are used, the next instruction would not be processed until the required speed is achieved. This may add to the overall duration of the test.

Where an instruction requires a change of speed over a period longer than the natural response lag, the software would artificially extend the change to produce a smooth ramping of the speed over the specified period.

4.4 XML file format

The format proposed follows the sequential nature of the instructions in a test. Each test is represented by a `<GaiaSpeedTest>...</GaiaSpeedTest>` element, and each instruction in the test is a child node. Each

`<instruction>...</instruction>` element must have an

`<action>...</action>` element, and may have `<duration>...</duration>` and

`<rpm>...</rpm>` elements.

The XML example below corresponds to the following set of instructions:

Start drive

Accelerate up to 1000 rpm over 10s then spend 60 seconds at speed

Accelerate up to 1010 rpm over 2s then spend 60 seconds at speed

Accelerate up to 1050 rpm over 5s then spend 60 seconds at speed

Decelerate to zero over 10 seconds

Stop the drive and disable

```
<GaiaSpeedTest>
  <id>15</id>
  <description>A sample test</description>
  <instruction>
    <action>Start</action>
  </instruction>
  <instruction>
    <action>Acc</action>
    <duration>10</duration>
    <rpm>1000</rpm>
  </instruction>
  <instruction>
```

```

        <action>Con</action>
        <duration>60</duration>
        <rpm>1000</rpm>
</instruction>
<instruction>
        <action>Acc</action>
        <duration>2</duration>
        <rpm>1010</rpm>
</instruction>
<instruction>
        <action>Con</action>
        <duration>60</duration>
        <rpm>1010</rpm>
</instruction>
<instruction>
        <action>Acc</action>
        <duration>5</duration>
        <rpm>1050</rpm>
</instruction>
<instruction>
        <action>Con</action>
        <duration>60</duration>
        <rpm>1050</rpm>
</instruction>
<instruction>
        <action>Dec</action>
        <duration>10</duration>
        <rpm>0</rpm>
</instruction>
<instruction>
        <action>Stop</action>
</instruction>
</GaiaSpeedTest>

```

5 Manual mode

File Test Log Help

Auto Manual

Settings (A)

Up ramp time

Down ramp time

Speed

Enable Disable

Status (B)

Speed

Torque

Power

Actual parameters (C)

Name <input type="text"/>	Description
Name <input type="text"/>	Description
Name <input type="text"/>	Description
Name <input type="text"/>	Description
Name <input type="text"/>	Description
Name <input type="text"/>	Description
Name <input type="text"/>	Description
Name <input type="text"/>	Description

5.1 Notes

- A. The user can set three parameters directly: up and down ramp times and speed. The ramp times are used to calculate the appropriate ramp parameter setting (see *Acceleration* section below).
- B. The status section highlights the main status values for the drive. These duplicate those in the parameter list.
- C. The values in this list are read directly from the inverter.

6 Test management module

When the user starts a test, many of the functions in the user interface are disabled, and control is passed to the test management module which loops through the set of instructions. The pseudocode below describes the main operation of the module.

```

for each instruction {
    compose appropriate inverter control message(s)
    send inverter message(s)
    while instruction not complete {
        poll inverter status
    }
}

```

The Weg inverter provides a large range of operating parameters which can be set and read over a serial channel. Some of these allow a ramp facility for acceleration and deceleration actions which means that the C# program only needs to wait for the instruction to complete rather than actively managing the duration of the action. See the *Acceleration* section below for details.

7 Inverter communications

Communications with the Weg inverter will use the Modbus protocol over an RS-232 serial connection. The inverter will be modelled as a C# class whose properties correspond to the inverter parameters that need to be read or updated during a speed test.

7.1 Setup

Those parameters that configure the inverter with the basic communications selections will need to be set manually using the front panel on the physical unit. These are shown in the table below.

Param.	Description	Value	Meaning	Default
P0202	Type of control	1	V/f 50 Hz	(Y)
P0220	LOCAL/REMOTE selection	2	L/R key	Y
P0221	Speed ref LOCAL	0	Keypad	Y
P0222	Speed ref REMOTE	9	Serial/USB	
P0223	FORWARD/REVERSE LOCAL	1	Always REV	
P0224	LOCAL run/stop	0	I/O keys	Y
P0225	JOG selection LOCAL	1	JOG key	Y
P0226	FORWARD/REVERSE REMOTE	1	Always REV	
P0227	REMOTE run/stop	2	Serial/USB	
P0228	JOG selection REMOTE	2	DIx	Y
P0308	Serial address	1	Device id	Y
P0310	Baud rate	0	9600	Y
P0311	Serial byte config	0	8 bits, no parity, 1 stop	
P0312	Serial protocol	2	Modbus RTU	Y

The setup configuration above assumes that the keypad on the front of the unit is the LOCAL condition and the serial connection is the REMOTE condition. Switching between the two is always done from the keypad. This provides a failsafe method for stopping the drive when under software control. To begin a software-controlled session, the inverter must be set to REMOTE using the keypad. Only then will the software commands to enable, disable, start and stop the inverter and to set the speed reference have any effect. The LOCAL/REMOTE setting determines where the inverter looks for its speed reference. In the LOCAL condition it will use the keypad setting (P0121), and in the REMOTE condition it will use the serial setting (P0683).

7.2 Initialisation

Further communications parameters are set

Param	Description	Value	Meaning	Default
P0133	Minimum speed ref	minRPM	Read from config table	
P0134	Maximum speed ref	maxRPM	Read from config table	
P0402	Motor rated speed	1000	Rated rpm	

7.3 Start action

The inverter is enabled but with minimum RPM. This action also set any other required parameters for the specific test.

Param.	Description	Value	Meaning
P0682	Serial control word	0x0000000000000011	Start and enable
P0683	Serial speed ref	minRPM	Minimum rotation

7.4 Acceleration

For acceleration actions, the user specifies a duration value. The inverter stores a ramp parameter which can be used to control the rate of acceleration. The parameter value stored by the inverter is the length of time to accelerate from 0 to maximum rpm. The duration of an acceleration event is therefore a function of current rpm, target rpm, maximum rpm and ramp. The task is to set the value of ramp (R) that will produce the required time interval (Δt) for a particular speed interval (Δrpm) and a given maximum speed (rpm_{max}). This is calculated by

$$R = \text{rpm}_{\text{max}} \frac{\Delta t}{\Delta \text{rpm}}$$

A further calculation is required to give the value of P0683, the serial speed reference. This is a 13-bit value which is calculated as a ratio of the required speed to the synchronous speed of the motor times a constant of 2000h (8192 decimal).

The synchronous speed of the motor is stored in P0402. The value of P0683 is given by

$$\frac{rpm \cdot 8192}{S}$$

where *rpm* is the required speed, and *S* is the synchronous speed of the motor.

Param.	Description	Value	Meaning
P0100	Acceleration time	calc	Based on duration
P0683	Speed reference	rpm	Speed read from UI

7.5 Deceleration

The duration of a deceleration action is controlled in the same way as that of an acceleration action.

Param.	Description	Value	Meaning
P0101	Deceleration time	calc	Based on duration
P0683	Speed reference	rpm	Speed read from UI

7.6 Stop action

The same inverter instruction is required for a normal stop action which follows a deceleration to 0 rpm, and for an interruption to the test run. If a test run is interrupted prematurely, the drive may still be rotating at high speed. To avoid tripping the inverter, it is therefore important to bring the drive to a stop over an extended period of time. The deceleration ramp is therefore set to a value which will stop the drive over 20s.

Param.	Description	Value	Meaning
P0101	Deceleration time	calc	Based on duration
P0682	Serial control word	0x0000000000000000	Stop and disable

7.7 Status polling

The status of the inverter is polled at the rate specified in the sampling period field in the user interface. Some parameter values need to be divided by 10 to get the actual value (eg. P0003). Any or all of the values in the table below can be retrieved.

Param.	Description
P0001	Speed reference
P0002	Motor speed
P0003	Motor current
P0005	Motor frequency
P0006	Inverter status
P0007	Motor voltage
P0009	Motor torque
P0010	Output power
P0050-89	Fault stack
P0090-95	Last fault details
P0316	Serial interface status
P0680	Logic status
P0681	Motor speed

7.8 Communications protocol

Weg uses the industry standard Modbus protocol for communicating with devices. Modbus is a general protocol which provides a wide range of communications features, only some of which are implemented by Weg. An even smaller range of messages are needed for this project.

8 Turbine controller communications

The Gaia Wind turbine provides a standard RS-232 communications channel over which a number of parameters can be monitored. The communications are provided

by an IC1000 controller system supplied by Mita Teknik who also defines a proprietary communications protocol called M-NET. This protocol has two versions, normal and extended, and older Gaia turbines make use of the normal version. The system therefore needs to be able to handle both. The major difference is that the extended version allows the polling of more specific information and the transmission of three commands, start, stop and reset whereas the normal version is entirely passive.

9 Additional features

9.1 Graphical output

The design includes a scrolling graphical trace of the speed and power from the two devices. This is implemented using the C# library by Stephan Zimmermann which is available from <http://www.codeproject.com/KB/miscctrl/GraphPlotting.aspx>

9.2 Excel export

The user needs to log test statistics to a file, ideally in Excel format. This functionality is provided by the Office Open XML library available from <http://excelpackage.codeplex.com/wikipage?title=Creating%20an%20Excel%20spreadsheet%20from%20scratch&referringTitle=Home>

Overall software design

The system requires a number of activities to be carried out simultaneously without interfering with each other. A multi-threaded design is therefore required which allows background tasks to be completed without preventing the user interacting with the interface. Both the inverter and the turbine controller are treated as subclasses of a generic serial device which is associated with its own thread. This allows each device to poll continuously for status information independently of any other activities. When a scripted test is being run, it also needs an independent thread so that the user can interrupt it if necessary, and the monitor function which updates the user interface with status information likewise runs independently. Along with the user interface itself, a total of five threads can be running simultaneously which can lead to timing and inter-thread communication issues.

Appendix L: Communications regarding data collection

Sent: 18 August 2011 11:21

To: Davison, Brian

Attachments:

2011_08_18_TestRun1.xlsx (77 KB)[Open as Web Page];

2011_08_18_TestRun2.xlsx (76 KB)[Open as Web Page];

Hi Brian,

Had to tweak the Run sequence a little to work with the new inverter set up, but other than that, the test run went well.

1	Start		
2	Acc	10	1005
3	Con	60	1005
4	Acc	2	1015
5	Con	10	1015
6	Acc	2	1025
7	Con	10	1025
8	Acc	2	1035
9	Con	10	1035
10	Dec	5	1000
11	Con	15	1000
12	Dec	5	986
13	Con	5	986
14	Dec	10	200
15	Stop		

First let me explain a few changes to the turbine behaviour with the new set up.

When the inverter detects a spinning turbine, it enables at the correct frequency to match rotation but at a lower voltage then ramps up the voltage. This feature makes it easier to test. Section 3, is there to give the turbine plenty of time to Ramp Up.

When this system is running at 50Hz and Power is <500W, the generator frequency is dropped to 49.5Hz by running at a lower speed we hope to try and squeeze a little bit more power out the turbine at the low end. So when slowing down, stage 11 @1000rpm is to allow the turbine to enter it's lower freq mode, you'll see a jump in power when that happens as this has increased the slip. Then when in low frequency mode if the turbine is producing < 500W the turbine will start to brake using the inverter. Section 13 is to make the turbine begin to try and slow, then finally stage 14 brings the turbine to a stop.

I'm keeping a track of bugs and thoughts on improvements. The one 'bug' I've found is that the Turbine power is displayed and logged as unsigned. It needs to be signed as the power can go negative. You'll see this in the attached log. Also drive power is being displayed correctly but not logged correctly.

Derek

Sent: 22 August 2011 15:38

To: Derek Robertson [Derek.Robertson@gaia-wind.com]

Attachments:

Report v3.docx (6 MB)[Open as Web Page]

Hi Derek

Here is a copy of the report. It's quite long, but you will probably be most interested in chapter 3 onwards. If you have any comments, please let me know.

You will see I've not complete the evaluation part yet. I was wondering if you could run the attached test script and let me have the output? To import it, use the import option on the File menu.

Thanks

Brian

Sent: 22 August 2011 15:39

To: Derek Robertson [Derek.Robertson@gaia-wind.com]

Attachments:

Rats.

Clicked the Send button instead of the attach button.

Here's the script.

B

Sent: 23 August 2011 07:41

To: Davison, Brian

Brian,

I'm currently testing out on site. Not sure I'll get a change to run this test before Thursday.

I'd assume that this isn't going to happen on time for now, If I get the opportunity to test I will do so and send the log ASAP.

I'll try have a read at your report today.

Thanks.

Derek

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